PN-ACY-719

Sustainable Transportation Guidelines

A Comprehensive Strategy to Efficient Municipal Transportation Planning

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PHYSICAL PLANNING INTERVENTIONS

The reasons for wishing to introduce interventions of a physical planning nature are that - by changing the actual transport infrastructure, there will be an accompanying change in exhaust emissions. To take this theory one step further, the generalized assumption has been made that if fuel consumption reduces, so do exhaust emissions.

In the future, therefore master planning for urban areas will be required to investigate and consider the relevance and validity of a number of planning interventions. These interventions have been shown to affect the fuel consumption in auto engines and the efficiency of traffic operations. It is well established that the most efficient form of travel in terms of fuel economy is when the vehicle is moving at a constant speed with limited acceleration or deceleration. There is evidence to show that the optimum speed of operation is around 40 kph. Therefore, the future planning of transport systems should incorporate those systems which encourage fewer stop/start conditions and reduced idling times and also to optimize cruising speed at peak hours in order to increase fuel efficiency and reduce exhaust emissions.

On this basis, it is recommended that Master Planners consider a series of possible concepts that will enable transportation systems to operate more effectively. It is important to realize that not all interventions will be pertinent to all cities and all areas. The spirit of this new Guideline is to present States and Cities with a shopping list of interventions, which should be considered so that individual cities can adopt those aspects, which are relevant to their particular situations.

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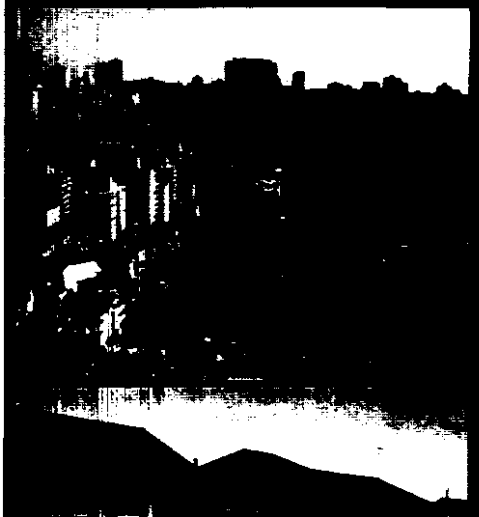
A. Land Use Management

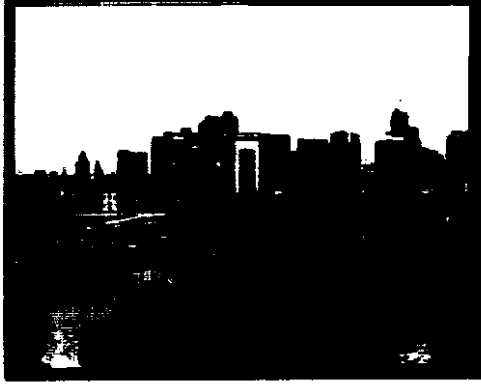
The optimization of land use planning and the creation of spatial distribution in order to reduce unnecessary travel is not new. In order to incorporate these principles into the Guidelines and encourage pollution reduction, the following issues should be considered.

Polluting uses such as power stations, cement plants, solid waste disposal sites and incinerators should be located on the fringes of urban areas and downwind of these developments.



Related land uses such as residential areas, schools and local clinics should be located in close proximity in order to encourage walking trips and reduce the need for vehicular movements.

The growth of local neighbourhood commercial centers should be encouraged so as to minimize the need for longer distance motorized travel.



Once the land use aspects of the Master Plan are fixed and agreed, the legislative basis should be reviewed in order to ensure that the planning authority has the power to enforce the land use patterns and to prevent non-conforming land uses from occurring.

B. Transport Network Management

Network management means studying and changing how the existing infrastructure is used so as to maximize the use of the transport infrastructure. In many Indian cities, the condition of most roads is below standard. As part of the emphasis on network management, master planners should investigate prevailing conditions and provide recommendations for improvements. In particular, the Master Plan should take account of the following issues:

a) **An inventory of all transport infrastructure should be made and should include:**

- Road provision by type and classification
- Non-motorized vehicle routes and lanes
- Bus and rail provision including bus lanes, fleet sizes and types, termini, stops/stations, signaling, maintenance yards and equipment
- Parking provision both of on street and off street spaces and classified by type
- Existence of paratransit including stock by type and fuel power

b) **A survey of all current travel patterns should be made. This survey should include the following:**

[redacted]

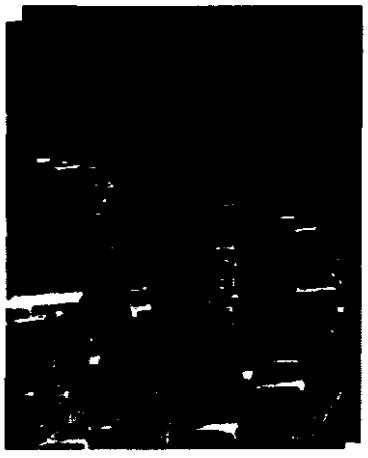
c) **The Master Plan should compare** the Supply [from a) above] with the Demand [from b) above]. This comparison should be made in order to identify the shortfalls in the existing system. The Master Plan should then enact such improvements as are necessary to create a balance between supply and demand or alternatively re-draft policy to effect changes in travel patterns.

d) **The cities should establish a hierarchy of highways** to govern the correct construction and operational standards ensure efficient traffic flow and minimize accidents.

e) **The Master Plan should assess** the effects which are caused by the balance of the system supply and demand. The result should consider how the existing infrastructure can be better used in order to promote the use of efficient transport.

f) **The Master Plan should investigate and identify** areas of the city in which new traffic circulation systems can be introduced. The introduction of one way systems will reduce conflicts and smooth flow conditions.

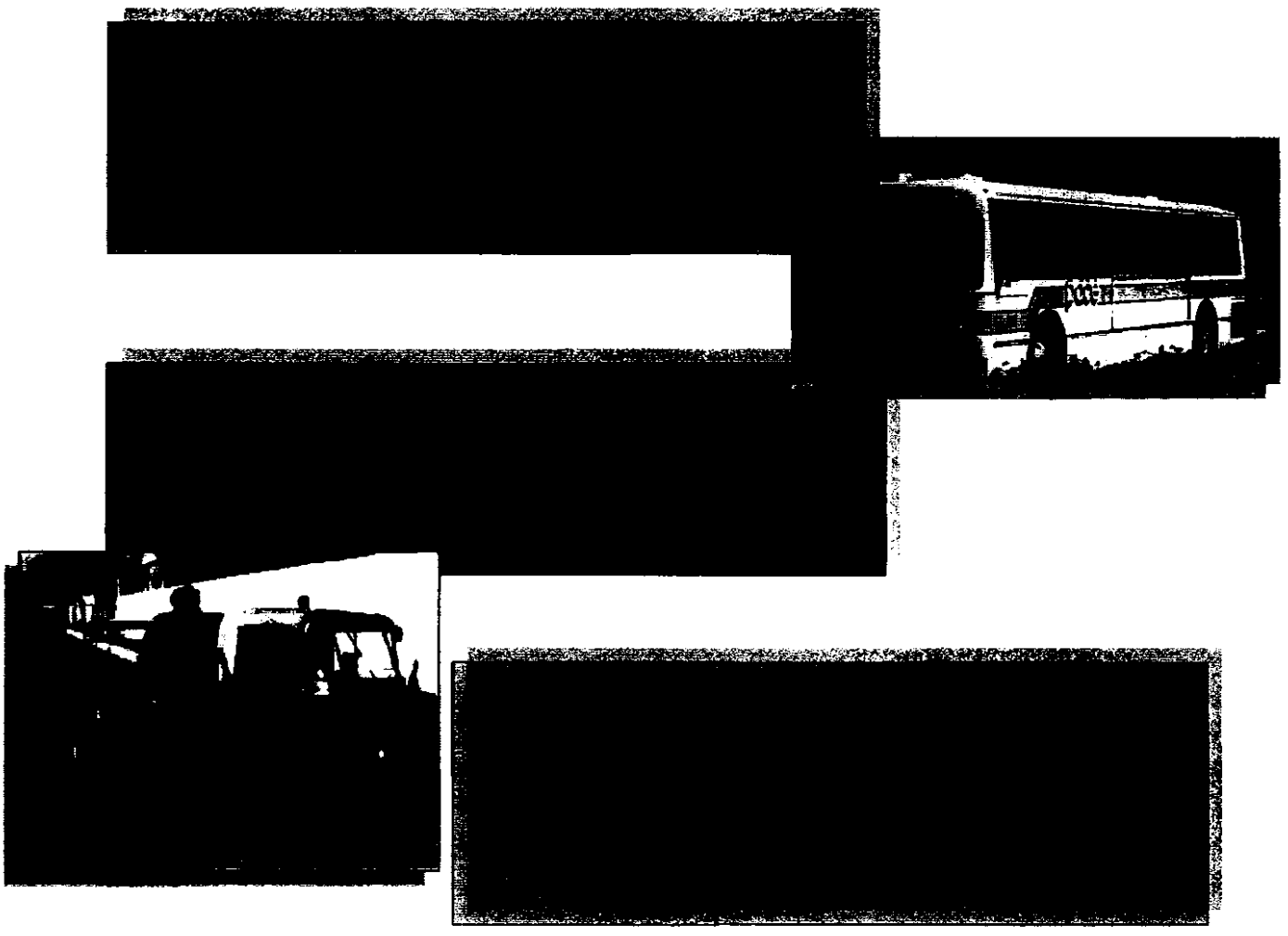
The Master Plan should consider all or some of the following:



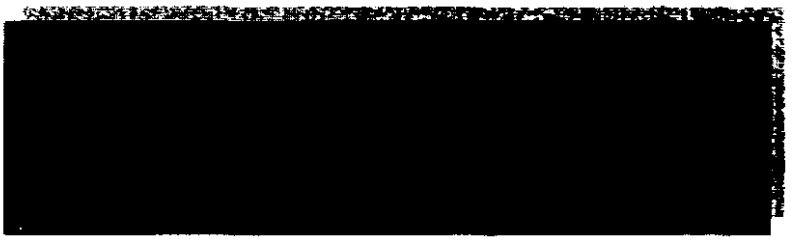
C. *Public Transport Provision*

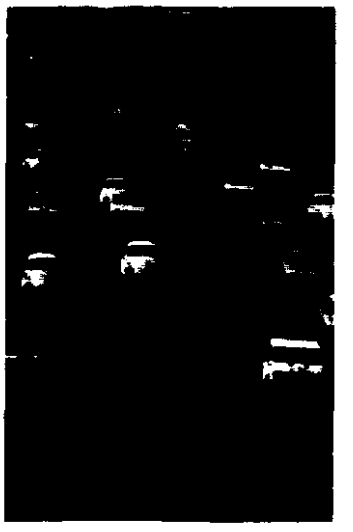
Public transport planning intervention has potentially the largest effect in terms of the recommendations of this Guideline. Research has been undertaken into the energy requirements of different modes of transport[1]. Figures show that the energy required per passenger kilometre for different modes is as follows – Passenger Car (0.7MJ), Train/Bus (0.25MJ) and Motorcycle (1.1MJ). It is clear from these statistics that the most energy efficient form of transport is the public transport mode, whether it is by rail or by bus. With public transport systems being about three times as energy efficient as cars, from the viewpoint of this Guideline, it is clear that the priorities should be placed on the public transport mode – rail, bus, paratransit and taxi.

In the master planning process, the role of public transport is central not only to mobility efficiency but also to the role of reduction in pollution. In particular the following aspects need to be considered:



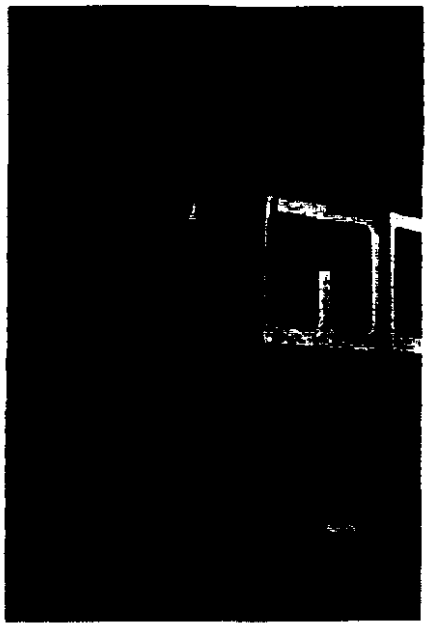
[1] *Figures above have been taken from a paper authored by Mr. Paul Proce from the Netherlands Institute of Urban Environmental Management.*

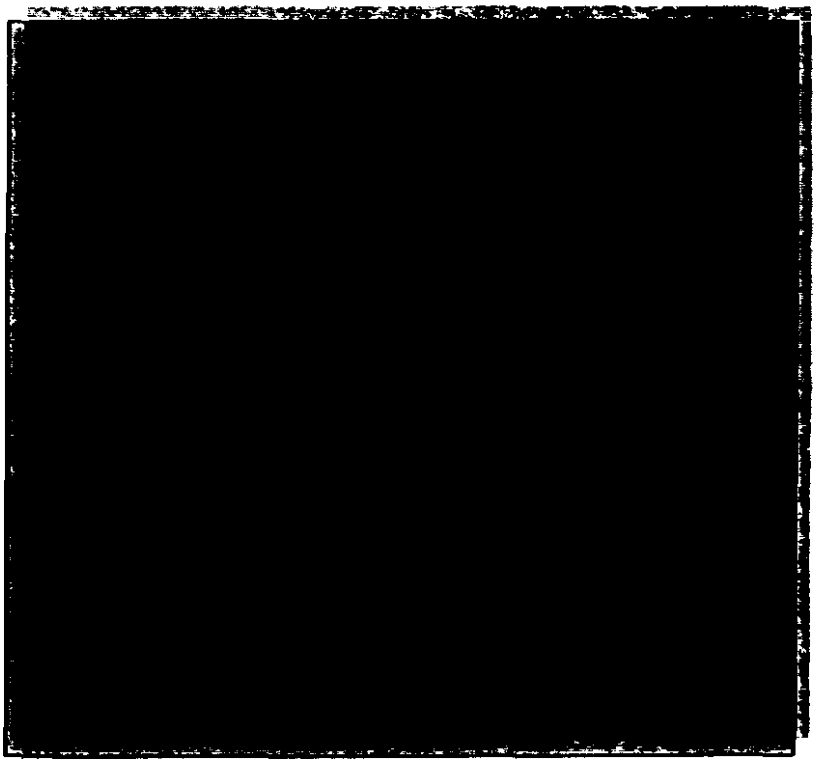


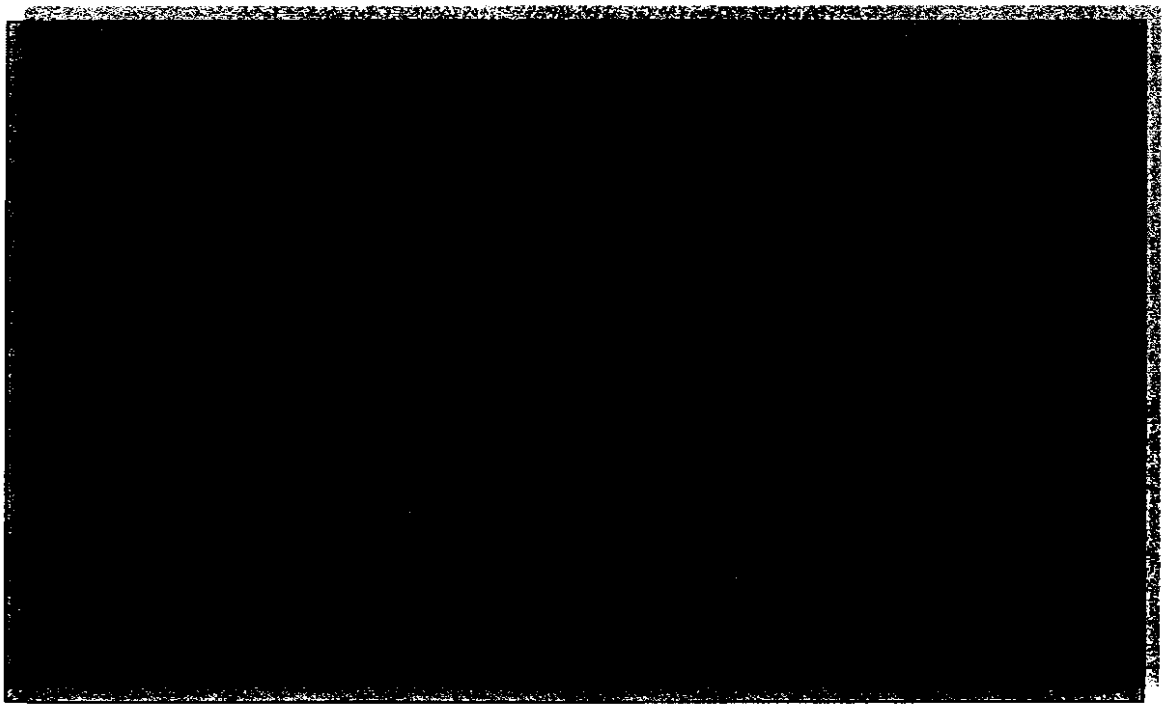


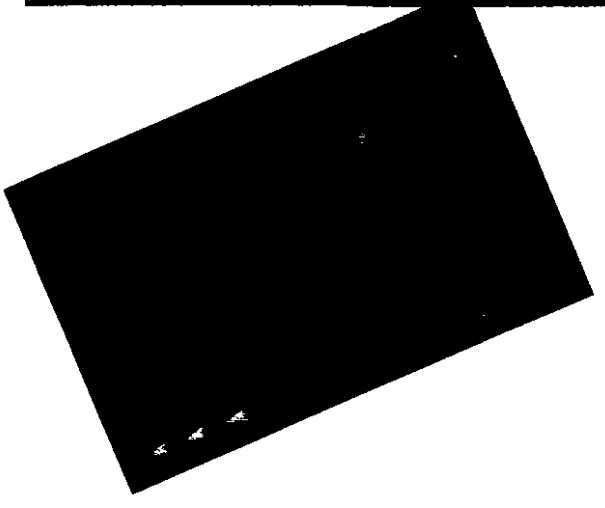
In some parts of the city, the plan should explore the benefits of restricting access and should include, for example, restrictions:

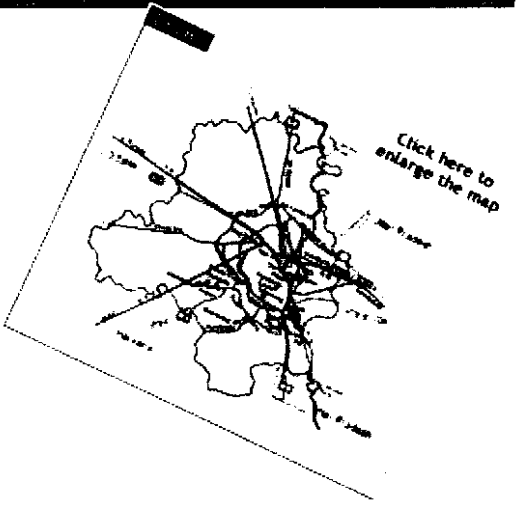
i) On certain vehicles due to size
ii) At certain times of the day to ease commuting congestion
iii) To entry by vehicles using gasoline power







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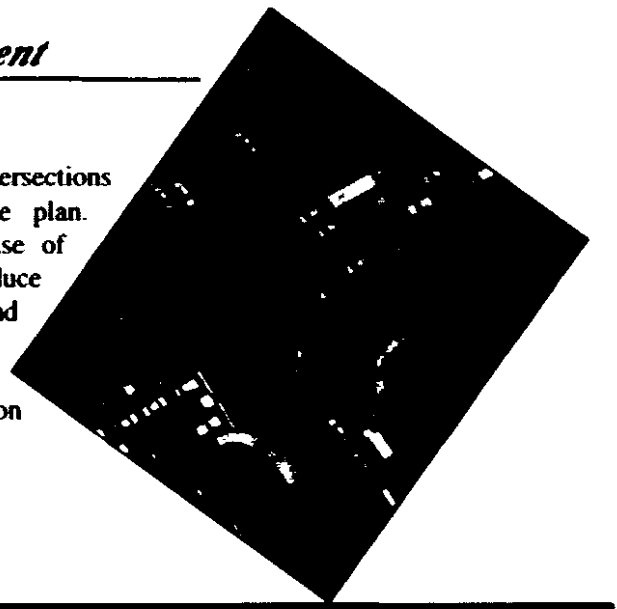
D. Road and Intersection Management



The use of traffic management techniques especially in intersections is of great importance in producing a pollution free plan. Intersections and their configurations are the main cause of delays in urban areas. Traffic management techniques reduce time wastage and pollution from idling vehicles and minimise conflicts.

The primary aspects to be considered for link and intersection planning include the following:

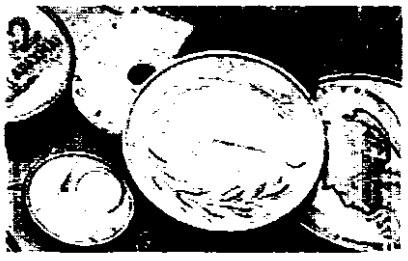
■	i) All on-street obstructions should be removed ii) Road cross-section should be made as consistent and uniform as possible iii) Mix of traffic should be identified by surveys iv) Slower moving and vulnerable traffic should be segregated from the faster moving
■	i) Simple lane delineations by paint markings ii) Low barrier kerbs iii) Reflectors and studs iv) Landscaped median separators
■	i) Levels of driver education ii) Levels of compliance with traffic laws iii) Clarity and strength of legislation and by laws iv) Likely levels of Police enforcement
■	i) Provision of bus stops with lay bys ii) Removal of sidewalk trading in certain areas iii) Prohibition of parking at certain points iv) Organised boarding and alighting areas for bus passengers v) Controls on goods vehicle loading at specific times vi) Well designated and signed pedestrian crossings vii) Provision of guard rails to prevent straying on carriageways

	i) Volumes of turning vehicular traffic ii) Space availability and/or limitations iii) Proximity of other intersections ii) Proximity of major traffic generators iii) Numbers of pedestrians crossing iv) Need for, and quality of, maintenance available in the area.
	i) Site lines and radii must conform with the current design standards ii) Turning traffic must be segregated so as to avoid conflicts iii) Segregation of turning traffic should be by pedestrian refuges or by clearly marked guide markings iv) Pedestrian crossing should be integral with stop lines and kerb radii v) Signing should be clear, legible and unambiguous
	i) Approach splays ii) Discharge width iii) Integration with pedestrian crossings iv) Adherence with the 'priority to the right' rule
	i) Approach splays ii) Discharge width iii) Integration with pedestrian crossings iv) Proximity to other intersections v) Linking in 'green wave' sequences vi) Demand responsive area-wide systems

E. Demand Management

One desired result of incorporating sustainable transportation concepts into the master planning process is to change the public's selection of its preferred mode of travel. The interventions are designed to move travel choice away from private vehicles and towards the public transport mode. The interventions noted above will achieve some successes. However in the longer term, a city should consider some form of Demand Management. This will have a much more significant affect upon the choice of travel mode. The concept behind Demand Management is that planning interventions are created that not only favour the public transport mode over the private transport mode but they will affect the total travel numbers and also change the timing of travel so as to spread the peak flows. All of these effects are created within Demand Management, largely by the use of pricing mechanisms, but also by some physical planning actions.

In the consideration of the overall Master Plan, the authorities should consider the following main issues within this subject area.



[redacted]

[redacted]

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F. The Need for Integration

[redacted] Traffic interventions within the physical planning sector can be an effective tool in reducing pollution on their own merits. However, even greater success will result when the elements are integrated into a comprehensive policy. It is therefore required that individual cities and states should consider the ideas put forward and implement those that are most appropriate for the individual city using the Master Plan as the vehicle for implementation and control.

G. Conclusions on Physical Planning Interventions

The main conclusions to be drawn from previous study and research into these topic areas are that physical planning interventions do indeed contribute to reductions in greenhouse emissions. The improvements in traffic flow, the shifts in mode brought about by favouring public transport modes and the reductions in conflicts and time wastage all contribute to these reductions. As cities in India plan for continued rapid urban growth rates, the corresponding increase in motor vehicles, and the seemingly inevitable pollution, the guidelines laid out in this document are intended to provide Master Planners with suggestions and recommendations to develop a comprehensive strategy for their city's urban development that will assist in reducing the greenhouse gas emissions from urban transport.

VI. LOCALIZING INFLUENCES

All cities are not the same, however, and what is good for one city may not be the correct choice for another. Each city, therefore, should consider the shopping list of ideas presented and select from this list those items which can be most beneficially adapted to their specific situation.

Contributory Aspects

The factors which contribute to changes in the perception of the above interventions are as follows:

- Temperature, Humidity and Wind. India has a hot humid climate in summer months. The northern areas become cold in winter and the southern areas stay warm and less humid. Of course, the monsoon affects all areas, and sometimes with serious consequences. The location of the city and its climactic conditions can affect the concentrations and dispersion of noxious gases. Wind has an obvious effect and costal cities will be more dependent upon this than some inland areas.

- Topography. Comparisons between hilly and flat cities will reveal a tendency to have different proportions of lower powered vehicles (typically fewer auto-rickshaws in the hilly cities). The tendency to replace power with fuel economy by changing engine compression ratios and adding illegal fuels to the petroleum will be prevalent in flat areas but may not be a problem in hilly cities.

- Fuel Availability. There is universal supply of petroleum and diesel fuels. However other fuels are less available to some cities and this may affect the conversion programme and the future planning. More advanced fuels requiring supply, for example, by pipeline may place these fuels outside the scope of some city's future plans.

VII. STEPS TO IMPLEMENTATION

This document is intended to provide guidance and recommendations for Master Planners to assist them to reduce the rate of growth of greenhouse gases from the transport sector even as they respond to the rapid pace of urban expansion.

A. The Physical Planning Process

There are existing processes in place that are used by cities to govern the way that the annual development plans are made. This Guideline is intended to supplement these procedures and not to supersede them. Whereas the existing procedures focus on strategic issues and macro developments for the city as a whole, the intervention recommendations that are covered in this document focus on addressing urban air pollution by the reduction of greenhouse gases from urban transport.

B. Establishment of Reviews

The scope of these new requirements will bring forward the need for cities to embark on new areas of study. Clearly there is a need for environmental specialists and also for traffic management experts. It may be that some cities are not yet ready for this new work effort; others will already be embarking upon the work with vigour. The states and cities may need to review structures and systems to decide how to accommodate new requirements. Training programs, new expertise and possibly even new departments may be required.

C. Time Scale for Completion

Typically master plans are developed for 20 year periods with an interim target years of 5 years and 10 years. This time frame is compatible with these new guidelines. Efforts to achieve major turnarounds in planning are a long term process. There can be, however, short term results that occur within the first 5 years. Primarily from the city's viewpoint, these improvements can result from the introduction of low cost traffic management measures. In parallel and outside the city's influence will also be national policy directions that will guide municipal actions and planning decisions, e.g. the adoption of specific alternative fuels.

D. The Urgency for Action

There is a worldwide acknowledgment that exhaust emissions and greenhouse gases in particular are a major threat to health in urban settings. This Guideline, therefore, seeks to accelerate the work already taking place in some cities and assist efforts in those cities which have yet to begin to focus on reducing urban transport emissions. The Guideline also aims to coordinate knowledge and efforts to the common good so that successes and lessons learned in one city are transferred to others.

ANNEXES

Annex A

Anthropogenic Emissions from Energy Activities in India: *Generation and Source Characterization*

Part II: Emissions from Vehicular Transport in India

India

Anthropogenic Emissions from Energy Activities in India: Generation and Source Characterization

Emissions from Vehicular Transport in India

Part II

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Anthropogenic Emissions from Energy Activities in India: Generation and Source Characterization

Part II: Emissions from Vehicular Transport in India

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Anthropogenic Emissions from Energy Activities in India: Generation and Source Characterization

Part II: Emissions from Vehicular Transport in India

Introduction

Part II of this research involves emissions from vehicular transport using petroleum fuel. Part I contained emission estimates of greenhouse and other trace gases including suspended particulate matter and soot carbon from India's coal-based thermal power plants. The United States Agency for International Development/India's Office of Environment, Energy & Enterprise has sponsored the project, *Anthropogenic Emissions from Energy Activities in India*, to assess the emissions of greenhouse and other trace atmospheric gases from energy activities in India.

This study is part of an effort to look at India's present and projected emission inventory, study the transport and distribution patterns of emitted pollutants, and develop a long-term air quality database covering the country's various geographical areas.

Petroleum Fuel Consumption in India

India's population, the second largest in the world, grows at a rate of about 2% per year[1] and has grown from 300 million in 1947 to more than a billion today. Rising population and changes in lifestyles consistent with rapid economic growth have accelerated the demand for all kinds of energy. Major sources of energy in India include coal, petroleum, biomass, nuclear power, and hydropower. Hydropower and nuclear power are less than 25% and 4%, respectively, of the total installed capacity. Fossil fuels -- coal and petroleum -- fulfill the remaining demand for energy. However, combustion of these fuels is the main source of pollution in the natural environment and is also considered responsible for global warming. Part I of this research discussed the emissions from coal-fired thermal power plants in India. This report deals with emissions from petroleum fuels used for vehicular transport in India.

The consumption of petroleum and consequent carbon dioxide (CO_2) emissions for the USA, China, and India are given in Tables 1 and 2 for 1990-1999, with projections up to 2020. Figures 1 and 2 show the petroleum fuel usage and corresponding CO_2 emissions during 1991-2000 respectively for the USA, China, and India. Petroleum fuel usage in India has grown from 1.2 million barrels per day in 1991 to 1.9 million barrels per day in 1999. The Energy Information Administration (EIA)[2] has projected an average annual percentage change (AAPC) in petroleum oil consumption as 4.3 and 3.7, and in CO_2 emissions from petroleum fuel use as 4.6 and 4.3 for India and China, respectively.

Table 1: Petroleum Oil Consumption (Million Barrel per Day)

Country	1990	1998	1999	2005	2010	2015	2020	AAPC
USA	17.0	18.9	19.5	21.3	23.2	25.1	26.7	1.5
China	2.3	4.1	4.3	5.3	6.8	8.6	10.5	3.7
India	1.2	1.8	1.9	2.5	3.2	4.1	4.9	4.3

[1] World Development Indicators – Annual report of the World Bank on development indicators (www.worldbank.org/data/wdi2000/pdfs/tab3-7.pdf, tab3-8.pdf, and /countrydata/aag/ind-aag.pdf)

[2] www.eia.doe.gov

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Figure 1: Growth of Petroleum Consumption in the USA, China, and India

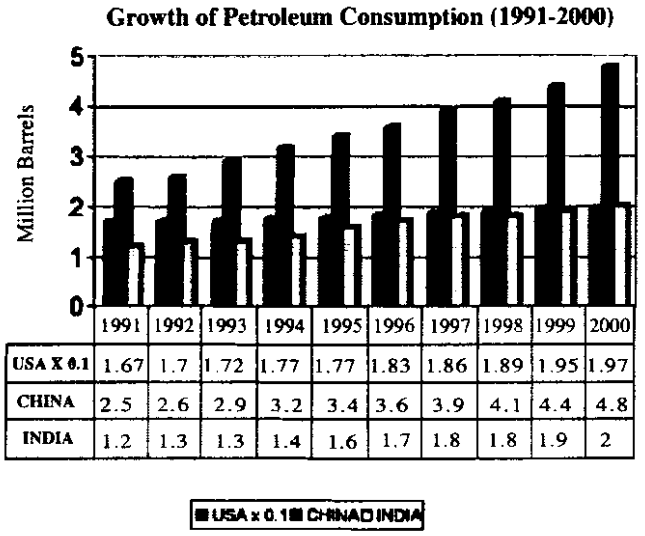
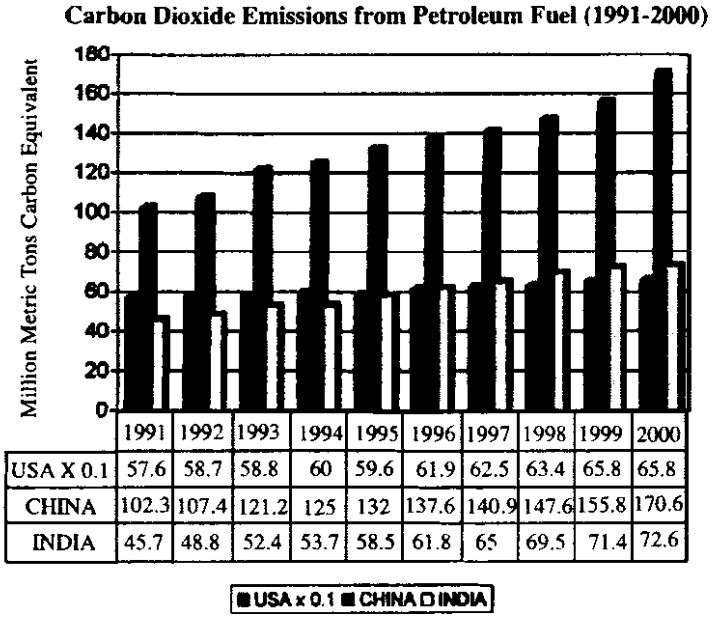


Table 2: Carbon Dioxide Emissions from Petroleum Fuel Use
(Million Metric Tons Carbon Equivalent)

Country	1990	1998	1999	2005	2010	2015	2020	AAPC
USA	590	635	650	705	711	835	891	1.5
China	94	152	160	196	251	317	390	4.3
India	45.0	69.5	71.4	85.3	106.7	131.6	157.6	4.6

Figure 2: Growth of Carbon Dioxide Emissions from Petroleum Fuel in the USA, China, and India



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Vehicular Transport in India

Many vehicle types are used in India for transporting goods and passengers. These vehicles use different types of internal combustion (IC) engines and petroleum fuels like gasoline (commonly referred to as *petrol* in India) and diesel. A broad classification of vehicles for the purpose of emission inventory can be made as:

(1) Two-Wheeler (2W)
(2) Three-Wheeler (3W)
(3) Car and Taxi (4W)
(4) Bus and Truck (B&T)

Table 3 gives the population and the effective daily distances[3] traveled by these vehicles in kilometers per day (km/day) in India's seven major cities and also for the entire country for the year 1997.

Table 3: Population (P: in thousands) and Distance Traveled (D: km/day) by Vehicles

	2W*		3W**		4W#		B&T###		All Vehicles##
	P	D	P	D	P	D	P	D	
Delhi	1,992	39	80	69	782	43	179	127	3,033
Mumbai	355	38	113	64	347	43	34	106	860
Kolkata	299	18	10	50	271	43	68	105	664
Chennai	713	39	41	56	185	43	26	100	975
Bangalore	839	36	74	69	167	45	29	98	1130
Hyderabad	712	31	57	54	93	40	21	70	887
Ahemdabad	530	31	44	54	87	30	24	70	686
All India	28,342	24	4,125	52	5,056	33	3,064	82	40,939

*includes two-stroke and four-stroke engines
** includes two-stroke and four-stroke engines
# includes cars, taxis, and jeeps
also include tractors, trailers and other vehicles
includes buses and trucks
P: Population of the vehicle in thousands
D: Effective daily distance[3] traveled (km/day) by vehicles

Estimating Emission from Vehicular Transport

The main emissions from IC engines used in vehicular transport are carbon monoxide (CO), CO_2, nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), carbonaceous material (soot), hydrocarbons (HC), and other trace gas species. Emissions of these pollutants depend on the combustion technologies, fuel used, intake air, engine conditions, and possible technologies that are used to control emissions.

Concentrations and mass emission factors[a] of CO, CO_2, SO_2, nitric oxide (NO), PM soot, and HC in the exhaust emissions from each of these vehicles are computed using basic principles of combustion and respective Indian driving cycles. HC emissions in the exhaust are considered only from scavenging[b] in the two-stroke engines. HC emissions due to oil leakage are not taken into account in the present analysis. Concentration values depend on the chemical composition of the fuel (gasoline or diesel) and the air-to-fuel ratio. The mass emission factor depends additionally on fuel consumption at different speeds including the idling stage. These are calculated for Indian driving cycles from the computed values of emissions. Kilometer traveled per unit of time for different vehicles is based on industry standard Indian Driving Cycle (IDC) as given in Appendix-A.

[3] Personal communication
[a] Pollutant species mass per unit of time or distance
[b] Operation of clearing the cylinder of burned gases and filling it up with fresh mixture of air and fuel

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Vehicles considered are:

1.	Two-wheeler two-stroke (2W2S)	5.	Four-wheeler gasoline (4WG)
2.	Two-wheeler four-stroke (2W4S)	6.	Four-wheeler diesel (4WD)
3.	Three-wheeler two-stroke (3W2S)	7.	Heavy-duty diesel low sulfur (HDDLS)
4.	Three-wheeler four-stroke (3W4S)	8.	Heavy-duty diesel high sulfur (HDDHS)

Tables B1 and B2 in Appendix-B give the computed and measured mass emission factors respectively for these vehicles. Table B3 provides the Indian norms for mass emission factors for the vehicles.

Species Emissions

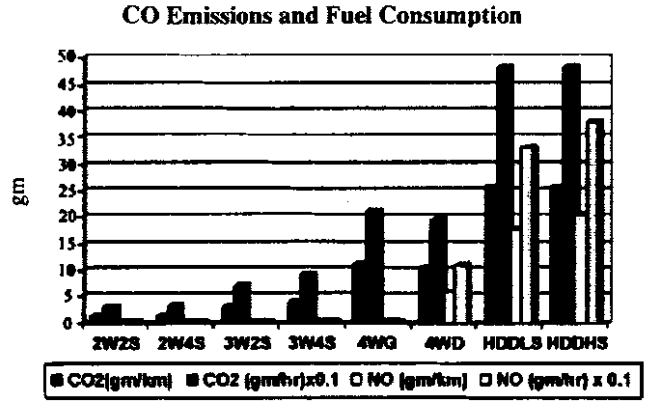
Species emission characteristics from different vehicles are discussed and compared with available measurement values.

Carbon Monoxide Emissions

CO results from the incomplete oxidation of fuel to CO_2. The most important parameter influencing CO emissions is the air-fuel ratio during engine operation. CO emissions increase with a decreasing air-fuel ratio. Gasoline engines often operate close to stoichiometric[c] at part load and fuel rich at full load. As a result, CO emissions are significant from gasoline engines. Diesel engines operate well on the lean side of stoichiometric, thus, CO emissions from diesel engines are minimal. The computations show that CO emissions from 2W2S vehicles are 2.0 gm/km compared to 1.16 gm/km for 2W4S vehicles. CO emissions from 4WG vehicles are computed as 24.75 gm/km, from 4WD vehicles as 2.0 gm/km, and from HDDHS vehicles using diesel fuel as 4.45 gm/km.

As Tables B1, B2, and B3 show, computed CO emissions are comparable with the norms for 2W2S engines, underestimated for 2W4S engines, overestimated for 3W2S engines, and underestimated for 3W4S engines. Computed CO emissions for diesel vehicles are comparable with the norms. One reason for this discrepancy might be the difference in quantity of fuel consumption at different speeds as prescribed by the manufacturers and considered by the agencies setting the norms. The computed values of CO emissions and fuel consumption are shown in Figure 3. Annual CO emissions in the year 1997 from all the vehicles are estimated as 2.163 million tons.

Figure 3: CO Emissions and Fuel Consumption by Indian Vehicles per IDC



[c] Amount of air needed for complete combustion of fuel

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Carbon Dioxide Emissions

All the carbon in the fuel should be oxidized to CO_2 in an ideal condition. However, part of the carbon does not get completely oxidized and is emitted either as carbonaceous material or as CO. CO_2 emissions increase with fuel consumption, hence, heavy-duty vehicles have much higher CO_2 emissions.

Calculated values of CO_2 emissions from the vehicles are given in Table B1. CO_2 emissions for 2W2S and 2W4S vehicles are estimated as 26.6 and 28.3 gm/km respectively. These estimates are lower than the measured values. For 3W2S and 3W4S vehicles, CO_2 emissions are estimated as 60.3 and 78.5 (gm/km) respectively, which are higher than the measured values. Estimates for CO_2 emissions from 4WG vehicles of 223.6 gm/km are slightly higher than the estimates of 208.3 gm/km from 4WD vehicles. CO_2 emissions per kilometer from buses and trucks are 515.1 gm/km, which are more than double the emissions from 4WG or 4WD vehicles. No norms or measurement values are available in India for CO_2 emissions from vehicular transport.

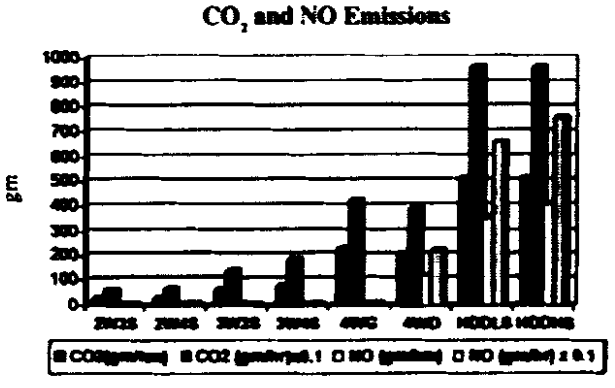
Figure 4 shows the CO_2 emissions (gm/km) and (gm/hr) from the Indian vehicles along with NO emissions. Total CO_2 emissions are estimated as 42.884 million tons from all vehicles in the year 1997.

Emissions of Oxides of Nitrogen

Nitrogen dioxide (NO_2) and NO grouped together are known as NO_x. NO_2/NO ratios are negligibly small for gasoline engines. Diesel engines have a relatively higher percentage of NO_2. NO is formed during combustion as the high flame temperature breaks down molecular oxygen and nitrogen of the inducted air, which then recombine to form NO. Reactions forming NO are temperature dependent, and, hence, NO emissions are relatively low during engine start-and warm-up phases. NO concentrations are higher for slightly lean mixtures. Dilution of the charge by residual gas or by moisture in the inlet air reduces NO concentrations.

Estimated values of NO are higher than the measured values, as the calculations are based on a constant temperature of 2500 K. Diesel engines run on the lean side (higher air to fuel ratio), and, hence, estimated values of NO are much higher for 4WD vehicles (116.9 gm/km) compared to 4WG vehicles (3.3 gm/km). NO emissions from buses and trucks are very high at 354.3 to 405.3 gm/km. Total NO emissions from all the vehicles in the year 1997 are estimated as 4.829 million tons. NO emissions are shown in Figure 4 along with CO_2 emissions.

Figure 4: CO_2 and NO Emissions by Indian Vehicles per IDC



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Hydrocarbons Emissions

Unburned hydrocarbons result from multiple processes during which fuel escapes the main combustion event. Oil leakage also results in HC emissions. Emission of HC from two-stroke engines during scavenging of unburned fuel for premixed type engines is a major problem. The exhaust from a two-stroke engine contains both unreacted fuel that did not burn or react at all, and as organic compounds formed from partial reaction of the fuel molecules. Oil added to the fuel or air stream to lubricate a piston in a two-stroke engine also may not fully burn. In four-stroke engines, the main source of HC emissions is fuel-air mixture in crevices[d].

HC emissions from two-stroke engines are estimated as 6.6 gm/km and 152.7 gm/hr from two-wheeler vehicles and 5.9 gm/km and 137.8 gm/hr from three-wheeler vehicles. The estimated values are higher than the measured values from the manufacturer[3]. HC emissions are estimated as 1.485 million tons from all the vehicles with two-stroke engines for the year 1997.

Sulfur Dioxide Emissions

The sulfur is oxidized during the combustion process to produce SO_2. A fraction of SO_2 is oxidized to sulfur trioxide, (SO_3); which combines with water to form a sulfuric acid aerosol. Gasoline fuel has a negligible amount of sulfur, therefore, SO_2 is not computed for gasoline vehicles. Diesel fuel in India contains sulfur between 0.05 and 0.5%. SO_2 emissions increase with fuel consumption as all the sulfur in the fuel is assumed to have oxidized in the combustion process.

SO_2 emissions are estimated as 10.3 gm/km for passenger cars with diesel engines, while for buses and trucks using high sulfur diesel, SO_2 emissions are estimated as 25.4 gm/km. In metropolitan Delhi, where low sulfur diesel is used, SO_2 emissions are estimated as 2.5 gm/km. SO_2 emissions from different vehicles are shown in Figure 6. Total SO_2 emissions in the year 1997 are estimated as 0.897 million tons.

Particulate Matter: Carbonaceous Material (Soot) Emissions

Incomplete and/or inefficient combustion processes of fuel generate carbonaceous material (soot); the lubricating oil also contributes some soot. Soot is formed under fuel-rich conditions. If anywhere in the engine cylinder there are fuel air pockets where the air-fuel mixture is very rich, there will be a tendency for the formation of species that include soot C(S), hydrogen cyanide (HCN), acetylene (C_2H_2), and methane (CH_4). This occurs normally in diesel engines. These species may freeze when mixed with leaner pockets or when the temperature drops, so these species can appear in the exhaust. With diesel engines, the maximum power is limited by the appearance of solid carbon (smoke and soot) in the exhaust, even though the engine is running lean. When the combustion is in the mixing controlled phase, the fuel passes through a very rich premixed reaction stage and then burns out in the turbulent diffusion flame at the edge of the jet. Most of the soot is burned with the fuel at the diffusion flame. The fraction of soot that is not oxidized becomes an exhaust emission.

Soot analysis ranges from C_8H to $C_{12}H$. Soot particles are essentially sub-micronic (i.e., less than one micron in size). A recent National Aeronautical and Space Administration's climate study[4] has found that large amounts of black carbon (soot) particles and other pollutants may be at least partially responsible for the change in the regional precipitation pattern.

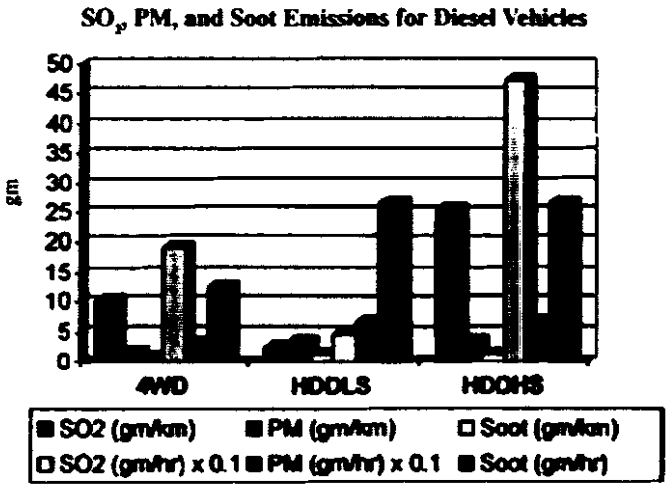
[d] A narrow region in the combustion chamber into which a flame cannot propogate

Diesel particulates consist primarily of combustion-generated soot on which some organic compounds have become absorbed. A high concentration of PM is manifested as visible smoke or soot in the exhaust gases. Some four-stroke engines with highly worn out piston rings or valve guides also lead to the emission of visible smoke due to an increased consumption of lubricating oil that fails to burn. Smoke forms in diesel engines due to heterogeneous combustion. Blue smoke consists mainly of oil and unburnt fuel, black smoke consists of soot, oil, and unburnt oil, while white smoke consists of water droplets and unburnt fuel.

Soot carbon is estimated as 42 gm/hr based on the composition and particulate emission value (105gm/hr) obtained by Needham et al.[5] for 40% load and 20 km/hr speed in a Turbo Charged Direct Injection (TCA DI) Engine (standard build). It may be noted here that for different speed and loads, particulate emissions have been reported to be different. The 40% load has been selected based on the average load observed by diesel vehicles in India in test conditions, and the average speed (i.e., 20 km/hr) is based on the BEST bus's average speed in Mumbai. The average speed for trucks is much higher than for buses. This provides a good basis for estimating PM and soot carbon. Otherwise, soot carbon from vehicles, so far, has not been measured or estimated in Indian conditions.

Soot emissions are estimated as 829 thousand tons while PM emissions are estimated as 2.073 million tons from all the vehicles in the year 1997. The estimated PM emissions (gm/km) from diesel vehicles are higher than the norms. PM and soot emissions from gasoline engines are negligible, and hence, are not considered in the analysis.

Figure 5: SO_2, PM, and Soot Emissions by Indian Vehicles per IDC



[5] 'Technology for 1994' J.R. Needham, D.M. Doyale, S.A. Faulner & H.D. Freeman, SAE Paper No. 891949

2

Emissions and Vehicles

The behavior of emissions, with time and distance traveled at different speeds for each vehicle type is discussed below. Tables C1 to C5 (Appendix-C) give the mass emission factor, as calculated with the present methodology for each type of vehicle at different speeds. Figures 9 to 13 (Appendix-C) plot the relation between emissions and speed.

Two-Wheeler Vehicles

India has a large population of two-wheeler vehicles. These vehicles are widely used for transportation in urban areas. Most two-wheeler vehicles have two-stroke engines, because of low initial and maintenance costs. These vehicles use gasoline fuel. CO and CO_2 emissions and fuel consumption (gm/km) are lowest at 30 to 40 km/hr speeds for 2W2S vehicles. NO emissions are higher at higher speeds but HC emissions also decrease with speed. *The ideal speeds for 2W2S vehicles would be between 30 to 40 km/hr. Improving the average speed of 2W2S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 17%, CO emissions by 36%, CO_2 emissions by 11%, NO emissions by 9%, and HC emissions by 46%. For two-wheelers, with the exception of NO, emissions are lowest at the cruising speed of 40 km/hr.*

Since the mid 1990s, 2W4S vehicles have also been introduced in India. These vehicles are used mostly for extra power and long distance traveling on rough roads. *Improving the average speed of 2W4S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 23%, CO emissions by 22%, CO2 emissions by 23%, and NO emissions by 21%. In 2W4S vehicles, 30 km/hr seems to be the optimum speed for lowest fuel consumption as well as lowest emissions for most of the pollutants, although NO emission decreases as the speed increases.*

Table C1 and Figure 9 (Appendix-C) show the values and variation of the species emissions at different speeds. Total emissions for the year 1997 from all the two-wheeler vehicles (two-stroke and four-stroke) in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)	HC (tons)
225 billion km	450,000	5,990,000	180,000	1,490,000

Three-Wheeler Vehicles

3W2S vehicles are very common in urban areas. These vehicles are used for conveyance as well as the transport of goods. Estimates of emissions for 3W2S vehicles show that CO, CO_2, and fuel consumption (gm/km) start increasing substantially for speeds lower than 20 km/hr and higher than 40 km/hr. NO emissions are low at all speeds but HC emissions also decrease with speed. *Hence, the ideal speeds for 3W2S vehicles would be 20 to 40 km/hr. Improving the average speed of 3W2S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 20% and CO, CO_2, NO, and HC emissions by 20%, 17%, 18%, and 56%, respectively. For 3W2S vehicles, 30 km/hr seems to be the optimum speed for lowest fuel consumption as well as lowest emissions with an exception of CO_2 emission.*

3W4S vehicles were not common until recently. Their usage is increasing due to HC emission concerns. CO_2 emissions from 3W4S vehicles are higher than those from 3W2S vehicles but CO and NO emissions are lower than those from 3W2S. *Present calculations show that improving the average speed of 3W4S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 25%, CO emissions by 78%, and*

CO_2 emissions by 22%. However, NO emissions will increase by 41%. In 3W4S vehicles, again the 30 km/hr speed seems to be the optimum speed although NO emissions are slightly higher at this speed while other pollutants' emissions are lower.

Table C2 shows the values, and Figure 10 (Appendix-C) shows the variation of the species emissions at different speeds for three-wheeler vehicles. Total emissions for the year 1997 from all the three-wheeler vehicles (two-stroke and four-stroke) in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)	HC (tons)
78.3 billion km	157,000	6,150,000	156,000	462,000

Four Wheelers

Population of four-wheeler vehicles is rapidly increasing in India, particularly in metropolitan cities. Earlier, mostly taxis were in use as four wheelers. With the availability of roads and because of other economic factors, the number of privately-owned four-wheeler vehicles is increasing every year.

Four-Wheeler Gasoline Vehicles

Gasoline fuel is most commonly used for four-wheelers. For 4WG vehicles, CO emissions are high but CO, CO_2, and NO emissions (gm/km) decrease with speed. Fuel consumption is lowest at 50 km/hr speed. *Present calculations show that improving the average speed of 4WG vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 25%, CO emissions by 79%, and CO_2 emissions by 22%. However, NO emissions will increase by 46%. Speeds between 40 and 60 km/hr would be ideal for 4WG vehicles.*

Emissions at different speeds for gasoline four-wheeler vehicles are shown in Table C3. Figure 11 (Appendix-C) shows the variation in the species emissions with speed. Total emissions from all the four-wheeler vehicles in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)
56.2 billion km	1,390,000	12,600,000	185,000

Four-Wheeler Diesel Vehicles

Four-wheeler vehicles using diesel fuel are in a minority though very popular with taxi and tour operators due to the low cost of diesel. These vehicles are used for extra power. For these reasons, the sale of these vehicles has been increasing steadily all over India. There are two types of diesel engine vehicles. Engines with direct injection (DI) of fuel are used in passenger cars, and engines with indirect injection (IDI) of fuel are used in jeeps and light commercial vehicles.

For these diesel vehicles, speeds greater than 40 km/hr are good for fuel economy as well as reducing emission of most pollutants. CO_2 and NO emissions from diesel vehicles are higher than from gasoline vehicles, but CO emissions are much lower. *According to present estimates, improving the average speed of 4WD IDI vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 52% and CO, CO_2, NO, soot, SO_2, and PM emissions by 53%, 52%, 38%, 22%, 52%, and 13%, respectively. Corresponding*

improvement for DI vehicles would be 37%, 38%, 37%, 36%, 25%, 37%, and 22%. For DI diesel vehicles, a cruising speed of 50 km/hr gives minimum emissions with the exception of CO_2. For IDI vehicles, again the cruising speed of 50 km/hr gives minimum emission, with an exception of NO. In general, speeds in the range of 40 to 60 km/hr are good for fuel economy as well as for reducing emissions of most of the pollutants.

Table C4 shows the values, and Figure 12 (Appendix-C) the variation of the species emissions at different speeds for diesel four-wheeler vehicles.

Buses and Trucks

In India, buses are the most common means of passenger transportation in urban cities and the intercity. Trucks are used to transport goods and mostly travel between cities. These vehicles use diesel fuel and mostly run overloaded. In the Delhi city area, a low sulfur diesel fuel is used. The driving cycle for buses and trucks should be different, but in these calculations the same driving cycle (industry standard) is used for both buses and trucks. Overloading has not been accounted for in the calculations.

As Table C5 shows, the ideal speed to reduce fuel consumption and emissions per kilometer for these vehicles is 40 to 60 km/hr. The sulfur dioxide emissions do not vary appreciably with speed. SO_2 emission (gm/km) would be 10 times lower for low sulfur diesel (used by vehicles in Delhi). *Present estimates show that even improving the average speed of the heavy-duty diesel vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 16% and CO, CO_2, NO, SO_2, soot, and PM emissions by 16%, 16%, 20%, 16%, 19%, and 20%, respectively. Improving the average speed from 25 km/hr to 35 km/hr will further reduce the emissions and fuel consumption by approximately 8%.*

Table C5 gives the emission values and Figure 13 (Appendix-C) shows the variation at different speeds for buses and trucks. Total emissions from all the diesel buses and trucks in India for the year 1997 are estimated as:

	Km traveled	CO (ton)	CO_2 (ton)	NO (ton)	Soot (ton)	SO_2 (ton)	PM (ton)
Buses	8.9 billion km	42,000	4,590,000	3,610,000	18690	226,000	934,500
Trucks	26.4 billion km	124,000	13,600,000	10,700,000	34,848	670,000	87,120

Vehicular Transport and Emission Trends

The vehicular population in India is rapidly increasing. Emissions per kilometer traveled and annual emissions are estimated based on available data. Figure 6 shows the kilometer traveled by different kinds of vehicles for 1990-1997.

Figure 6: Trends in Vehicular Transport (kilometers traveled) for 1990-1997

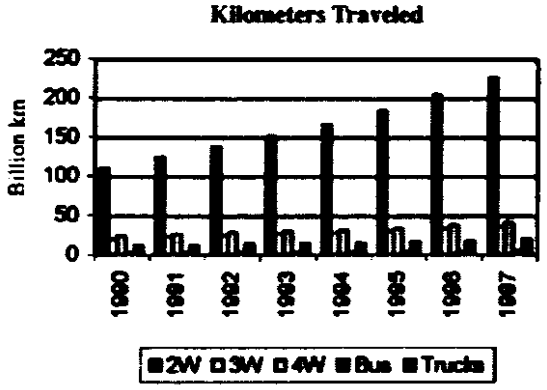
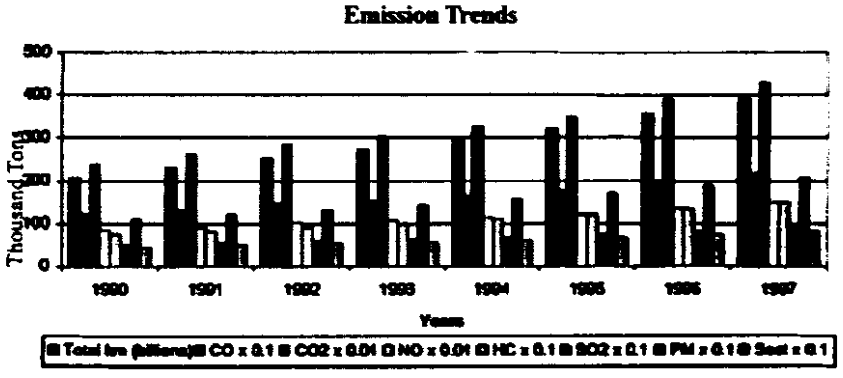


Figure 7 shows the computed annual emission estimates of different species and the total vehicle kilometer traveled for 1990-1997. Emissions per kilometer (with the exception for PM) are decreasing, while the total annual kilometer traveled and total emissions are increasing. Total kilometers traveled by all the vehicles increased by 92%, while the emissions such as CO increased by 80%, CO_2 and NO by 78%, PM and soot (black carbon) by 91%, and HC by 104%. However, a large increase in HC and black carbon emissions reflect a loss of fuel usage and needs the attention of owners, pollution controlling agencies, etc. Periodic maintenance to check the pollution levels is recommended.

Figure 7: Yearly Kilometers Traveled and Emissions (thousand tons) for 1990-1997



Emissions Scenario in Seven Metropolitan Cities

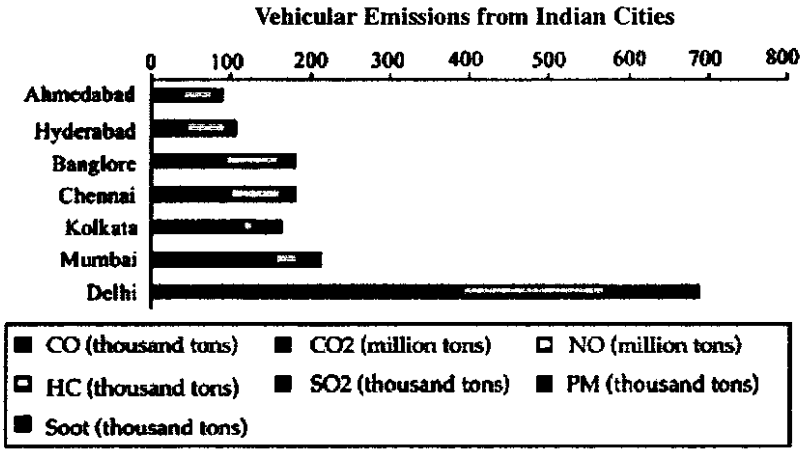
Table D2 (Appendix-D) provides emission estimates from transport sectors in seven major Indian cities for the year 1997. Using the computed emission factors, preliminary estimates of emissions from vehicular transport in seven Indian metropolitan cities are shown in Figure 8. Numbers about vehicle population and distance traveled, which are quoted in various published documents[6,7,8] are used to calculate cumulative emissions. These estimates are made for the year 1997, assuming that 5% of the total two-wheeler population is four-stroke, all the three-wheelers have four-stroke engines, diesel is of high sulfur content, and buses and trucks travel the same average distances as given in Table 3. Emissions from vehicles belonging to other categories have not been calculated and are not included in the city totals. The computed values show that transport-related emissions in Delhi are far more in comparison to any other Indian cities.

[6] Handbook of Urban Statistics 1995, published by National Institute of Urban Affairs, New Delhi

[7] TERI Energy Data Directory & Yearbook 2001/2002

[8] Transport Fuel Quality for Year 2005, published by Central Pollution Control Board, New Delhi, http.envfor.nic.in/cpcb

Figure 8: Cumulative Emissions from Vehicular Transport in Seven Mega Cities of India



Limitations of Calculations and Results

The calculations given in Table B1 are based on a theoretical ideal. Real conditions may differ from the ideal (theoretical) conditions. Gasoline is considered as $C_7H_{13}O_{0.1}$ and diesel as $C_{15}H_{34}N_{0.01}S_{0.05}$ for Delhi city and $C_{15}H_{34}N_{0.01}S_{0.5}$ for the rest of India. The Calculations have the inherent assumption of a new engine without any fuel or oil leakage, and the estimates do not account for engine deteriorations due to aging (Table D2) or vehicle overloads. No account is taken of any emission control devices such as catalytic converters (from 1997, the only control measure in place was the use of unleaded gasoline) to limit emissions. At present in India, catalytic converters are not mandatory for all the vehicles except in a few metropolitan cities. Hence, the estimates of species emissions for which control devices are used would be lower. Following are some other limitations:

- The automobile industry is a private industry in India. The data about fuel consumption and air-to fuel ratio at different speeds is considered proprietary. This data was made available to us as a personal communication.
- These values are computed based on the operation of a new engine. This means that perfect maintenance of the vehicles is assumed. The deterioration in engine performance relating to age is not taken into account.
- Other parameters that are not accounted for are road roughness and vehicle overload.
- HC emissions are from exhaust of two-stroke engines only. HC emissions while fueling the vehicle or from other sources are not accounted for this inventory.

Policy Relevance

The transport sector has been identified as one of the major sources of pollution in India's urban centers. Urgent actions are needed to implement viable policies to reduce the emissions of pollutants from this sector to reduce health hazards to human beings and to mitigate greenhouse gases emissions. Considering the growth of urbanization in India, it is important that this issue be dealt with immediately based on scientific knowledge. The urgency and importance are also reflected by the policy interventions already implemented in India.

A number of policy options are available to reduce the emissions of pollutants. These include both technical options (like changes in vehicle technologies and changes in fuel types and characteristics) as well as traffic management options. The latter can be easily implemented and provides a low cost option. The computed values for emissions of different pollutants from various vehicles as mentioned earlier clearly show that if traffic management increases the average cruising speed of the vehicles to 30 to 50 km/hr, it would result in a substantial decrease in the emission levels of most of the species. City authorities and urban local bodies throughout India can implement these measures for traffic management. Further, rising emission levels and traffic flow should be given consideration in long-term planning of land use by city authorities.

Next Steps/Recommendations

1. This study provides valuable tools for inventory preparation of emissions from vehicular transport in actual as well as simulated conditions. Simulations include changes in driving patterns, vehicles or technology, and fuel composition. Emission estimates are based on a theoretical ideal and the input data available from published information and personal communications. Currently, the methodology used in this study is most suitable for the conditions in India. The results provide a valuable benchmark. The exercise should be followed with efforts to increase accuracy with more realistic input information and verification/validation measurement.

2. To decrease emissions, traffic bottlenecks should be minimized, and optimum speeds (best fuel consumption per km and minimum emissions per km) should be prescribed.

3. Fuel quality has a big impact on overall emissions. The effect of fuel adulteration should be investigated. Similarly, the effect of fuel quality improvement such as blending 5% ethanol with gasoline and diesel can also be investigated using this tool.

4. With an increasing vehicular population and consequent pollution levels from the transport sector, state and local authorities should encourage the deployment of electric alternate fuel vehicles. Steps should also be taken to promote a robust public transport system to check the growth rate of pollution as well as to reduce congestion.

5. Dispersion and transport of emitted pollutants from different activities over the entire Indian region need to be mapped to better understand their impact on the climate, as well as on human, animal, plant, and ecological systems.

6. Further research is needed on population exposure to these polluting gases.

Some of these recommendations/suggestions call for additional studies. Dispersion and transport of emitted pollutants from energy activities over the entire Indian region and population exposure to these polluting gases will be part of the project's next phase. Analyses of detailed air characteristics and associated meteorological parameters will help us understand and illustrate the full impacts of greenhouse gases and other pollutants on human health and climate in India.

To learn more about emissions in India, please visit **www.osc.edu/pcrm/emissions**
or contact Moti Mittal, Director, Program for Computational Reactive Mechanics, at moti@osc.edu.

The Indian driving cycles (urban driving) for four-wheeler and two- or three-wheeler vehicles are given in Appendix-A (Tables A1 and A2). This also includes computed values of CO_2 emissions at different stages of IDC for different vehicles. Appendix-B indicates the computed, measured, and prescribed norms for mass emission factors. Appendix-C contains the computed values for different vehicles along with corresponding graphs. Appendix-D gives the emission estimates from major cities in India and the useful average life span of vehicles in India.

Appendix-A

Table A1: IDC for Four-Wheelers and CO_2 (gm) Emissions at Different Stages

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	I	1		0	11	11	5.16	5.18	10.26
2	A	2	1.04	0-15	4	15	3.11	3.42	6.95
3	SS	3		15	8	23	8.34	9.20	18.5
4	D	4	-0.69	15-10	2	25	1.74	1.95	3.98
5	D, CD		-0.92	10-0	3	28	1.64	1.71	3.44
6	I	5			21	49	9.86	9.90	19.59
7	A	6	0.83	0-15	5	54	3.84	4.25	5.53
8	GC				2	56	2.30	4.63	4.62
9	A		0.94	15-32	5	61	8.62	16.07	16.07
10	SS	7		32	24	85	51.32	93.04	93.05
11	D	8	-0.75	32-10	8	93	11.04	21.26	21.27
12	D, CD		-0.92	10-0	3	96	1.88	3.81	3.81
13	I	9			21	117	9.90	19.59	19.60
14	A	10	0.83	0-15	5	122	4.38	8.90	8.90
15	GC				2	124	2.30	4.62	4.63
16	A		0.62	15-35	9	133	15.86	29.65	29.65
17	GC				2	135	4.39	8.30	8.31
18	A		0.52	35-50	8	143	19.21	40.62	40.62
19	SS	11		50	12	155	30.86	69.87	69.88
20	D	12	-0.52	50-35	8	163	18.59	37.85	37.86
21	SS	13		35	13	176	28.56	53.98	53.99
22	GC	14			2	178	4.39	8.30	8.31
23	D		-0.86	32-10	7	185	10.42	19.87	19.87
24	D, CD		0.92	10-0	3	188	1.80	3.62	3.63
25	I	15			7	195	3.30	6.53	6.53

(1): Serial number
(2): Operation
(3): Phase
(4): Acceleration (m/s/s)
(5): Speed (km/hr) I: Idling

(6): Time (second)
(7): Cumulative time (second)
(8): CO_2 emissions (gm) for 4WG
(9): CO_2 emissions (gm) for 4WD
(10): CO_2 emissions (gm) for heavy-duty diesel vehicle

I: Idling
A: Acceleration
D: Deceleration
SS: Steady speed

GC: Gear change
CD: Clutch depressed
S: seconds

Cycle duration = 195 seconds
Number of cycle/test = 4
Total distance traveled = 1.013km x 4 = 4.052 km
Average speed (with idling) = 18.7 km/h
Average speed (without idling) = 27.01 km/h
Maximum speed = 50 km/h

Table A2: Indian Driving Cycle for Two- and Three-Wheelers

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	I	–	–	16	16	0.73	0.99	1.64	2.87
2	A	0.65	0–14	6	22	0.54	0.55	1.06	1.76
3	A	0.56	14–22	4	26	0.60	0.52	1.10	1.77
4	D	–0.63	22–13	4	30	0.54	0.49	1.01	1.63
5	SS	–	13	2	32	0.23	0.22	0.44	0.72
6	A	0.56	13–23	5	37	0.75	0.65	1.37	2.21
7	A	0.44	23–31	5	42	0.99	0.81	1.85	2.78
8	D	–0.56	31–25	3	45	0.58	0.48	1.07	1.63
9	SS	–	25	4	49	0.73	0.61	1.32	2.05
10	D	–0.56	25–21	2	51	0.33	0.28	0.60	0.96
11	A	0.45	21–34	8	59	1.62	1.32	3.05	4.55
12	A	0.32	34–42	7	66	1.95	1.62	6.81	5.68
13	D	–0.46	42–37	3	69	0.84	0.69	1.73	2.43
14	SS	–	37	7	76	1.86	1.50	3.75	5.31
15	D	–0.42	37–34	2	78	0.50	0.40	0.99	1.39
16	A	0.32	34–42	7	85	1.94	1.61	6.78	5.68
17	D	–0.46	42–47	9	94	2.15	1.74	4.24	6.15
18	D	–0.52	27–14	7	102	1.18	1.03	2.18	3.49
19	D	–0.56	14–00	7	109	0.44	0.48	0.89	1.50

(1): Serial number
(2): Operation
(3): Acceleration (m/s/s)
(4): Speed (km/hr)
(5): Time (second)
(6): Cumulative time (second)
(7): CO_2 emissions (gm) for 2W2S
(8): CO_2 emissions (gm) for 2W4S
(9): CO_2 emissions (gm) for 3W2S
(10): CO_2 emissions (gm) for 3W4S

Appendix-B

Table B1: Computed Mass Emission Factors for Different Vehicles

Species		2W2S	2W4S	3W2S	3W4S	4WG	4WD	HDDLS	HDDHS
FC	gm/km	11.0	9.7	22.1	25.9	84.3	92.7	195.2	195.2
	gm/hr	254.9	225.2	511.2	599.8	1576.5	1733.2	3649.9	3649.9
CO_2	gm/km	26.6	28.3	60.3	78.5	223.6	208.3	515.1	515.2
	gm/hr	617.0	655.6	1397.2	1817.1	4181.3	3896.4	9633.3	9634.8
CO	gm/km	2.0	1.4	5.25	2.0	24.8	2.0	4.7	4.7
	gm/hr	46.4	33	121.6	46.9	462.9	36.8	88.4	87.4
NO	gm/km	0.8	1.4	1.2	2.0	3.3	116.9	354.3	405.3
	gm/hr	20.5	32.9	28.1	46.0	62.4	2185.5	6626.6	7579.2
SO_2	gm/km	0	0	0	0	0	10.3	2.5	25.4
	gm/hr	0	0	0	0	0	192	47.4	474.4
HC	gm/km	6.6	0	5.9	0	0	0	0	0
	gm/hr	152.7	0	137.8	0	0	0	0	0
PM#	gm/km	0	0	0	0	0	1.56	3.3	3.3
	gm/hr	0	0	0	0	0	31.5	66	66
Soot	gm/km	0	0	0	0	0	0.63	1.32	1.32
	gm/hr	0	0	0	0	0	12.6	26.4	26.4

FC: Fuel consumption

PM: Particulate matter, values derived from Needham, et al. 1994

Table B2: Measured Mass Emission Factors (gm/km) for 1996-2000 period[9]

Species	2W2S	2W4S	3W2S	4WG	4WD	Buses	Trucks
CO	4	2.6	8.6	3.9	1.2	4.5	4.5
NOx	0.06	0.3	0.09	1.1	0.69	16.8	8.4
HC	3.3	0.7	7	0.8	0.37	1.21	1.21
PM	0.1	0.06	0.15	0.05	0.42	1.6	0.8

Table B3: Norms (India 2000) for Mass Emission Factors for Different Vehicles per IDC[9]

Species	2W2S gm/km	2W4S gm/km	3W2S gm/km	3W4S gm/km	4WG gm/km	4WD gm/km	Buses (Low S*) gm/kwh	Buses (High S) gm/kwh
CO	2.0	2.0	4.0	4.0	2.72	2.72	4.0	4.5
HC+NO_x	2.0	2.0	2.0	2.0	0.97	0.97	1.1-HC 7.0-NO_x	1.1-HC 8.0-NO_x
PM							0.15	0.36

*Low sulfur = Bharat (India) Stage 2000 (Norm applicable in metro cities only)

[9] M. Saxena, A.K. Jain, and S. Singhal, Science and Culture, Vol. 68, No.9-12, 2002

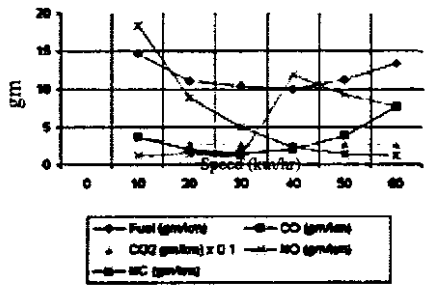
Appendix–C

Table C1: Emissions from Two-Wheeler Vehicles (2W2S and 2W4S)

Speed	0 (km/hr)		10 (km/hr)		20 (km/hr)		30 (km/hr)		40 (km/hr)		50 (km/hr)		60 (km/hr)	
	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S
FC (gm/hr)	87	76	146.5	120.3	220.5	164.7	309	209	412	310	560	540	800	806
FC (gm/km)			14.7	12.0	11.025	8.2	10.3	7.0	10.3	7.8	11.2	10.8	13.33	13.4
CO_2 (gm/hr)	165.4	222.1	361.8	352.6	558.2	483.2	754.6	613.8	1043.4	879.5	1340.9	1430.4	1608.1	2219.1
CO_2 (gm/km)			36.2	35.3	27.9	24.2	25.15	20.5	26.1	22.0	26.8	28.6	26.68	36.9
CO (gm/hr)	33.1	9.8	36.1	16.1	39.0	22.4	42	28.7	81.3	56.6	187.4	163.2	455.7	190.0
CO (gm/km)			3.6	1.6	1.95	1.1	1.4	1.0	2.03	1.4	3.75	3.3	7.59	3.2
NO (gm/hr)	1.9	12.0	11.5	20.4	21.0	28.8	30.6	37.1	471	30.3	463.1	27.5	455.7	56.5
NO (gm/km)			1.2	2.04	1.5	1.4	1.02	1.2	11.8	0.8	9.26	0.55	7.59	0.9
HC (gm/hr)	200.1	-	183.4		166.7		150		89.9		65.1		69.7	
HC (gm/km)			18.3		8.84		5.0		2.25		1.302		1.16	

Figure 9: Fuel Consumption and Exhaust Emissions from Two-Wheeler Vehicles

Emissions per km for 2W2S Vehicles



Emissions per km for 2W4S Vehicles

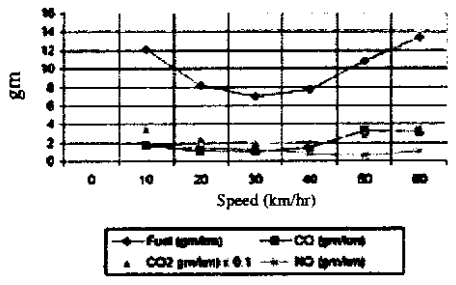


Table C2: Emissions from Three-Wheeler Vehicles (3W2S and 3W4S)

Speed	0 (km/hr)		10(km/hr)		20(km/hr)		30(km/hr)		40(km/hr)		50(km/hr)	
	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S
FC (gm/hr)	180	250	305	395	430	540	590	690	920	990	1580	1490
FC (gm/km)			30.5	39.5	22.5	27	19.7	23	23	24.8	31.6	29.8
CO_2 (gm/hr)	339	646.5	683.7	1152.4	1028.3	1658.4	1364.9	2135	2189.9	3056.4	8500.8	4533.5
CO_2 (gm/km)			68.4	115.2	51.415	82.917	45.49	71.2	44.75	76.5	170.	90.67
CO (gm/hr)	66.9	85.5	69.6	51.8	72.3	18.02	186.8	13.1	270.4	22.99	654.0	78
CO (gm/km)			7.0	5.2	3.615	.9	6.22	.434	6.76	.575	13.08	1.6
NO (gm/hr)	4	1.0	18.1	14.8	32.2	22.2	22.2	75.5	39.1	81.9	44.5	47.6
NO (gm/km)			1.8	1.5	1.61	1.1	.74	2.5	.98	2.5	.89	.95
HC (gm/hr)	210	-	180		150		100		90		120	
HC (gm/km)			18.0		7.5		3.33		2.25		2.4	

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Figure 10: Fuel Consumption and Exhaust Emissions from Three-Wheeler Vehicles

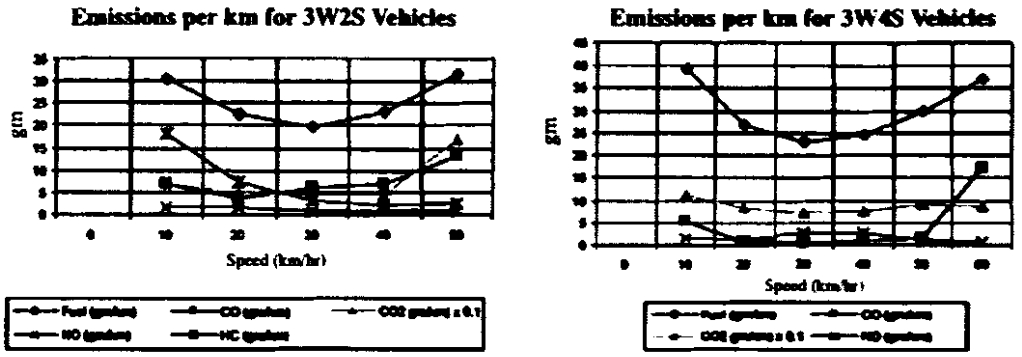


Table C3: Emissions from Four-Wheeler Gasoline Vehicles

Speed (km/hr)	0	10	20	30	40	50	60
FC (gm/hr)	600	1000	1600	2200	2720	3300	4200
FC (gm/km)		100	80	73.3	68	66	70
CO_2 (gm/hr)	1690	2870	4640	6380	6620	7240	8220
CO_2 (gm/km)		287	232	212.67	165.5	144.8	137
CO (gm/hr)	110	160	230	310	1190	1950	3120
CO (gm/km)		16	11.5	10.33	29.75	39	52
NO (gm/hr)	26	52	99	140	42	33	28
NO (gm/km)		5.2	4.95	4.67	1.05	0.66	0.47

Figure 11: Fuel Consumption and Exhaust Emissions from Four-Wheeler Gasoline Vehicles

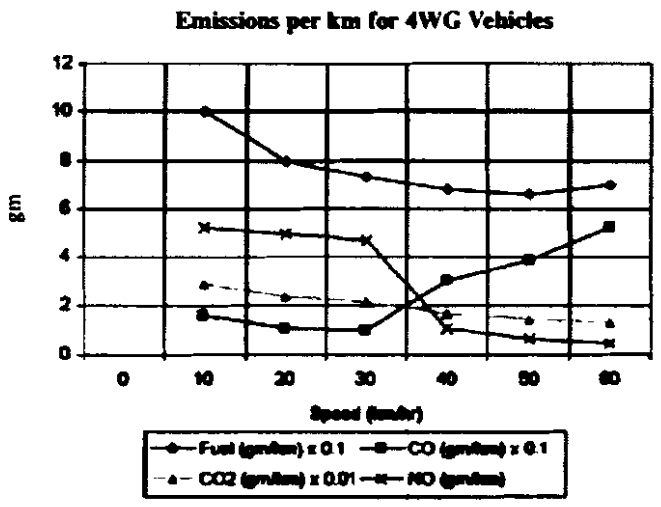
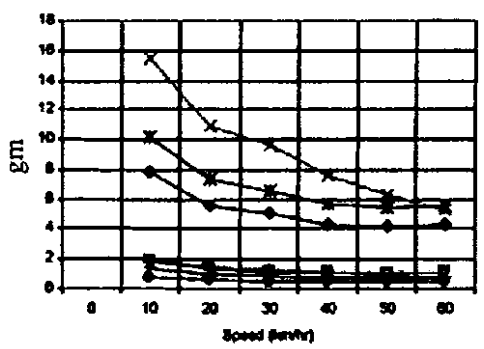


Table C4: Emissions from 4WD (DI and IDI Engine) Vehicles

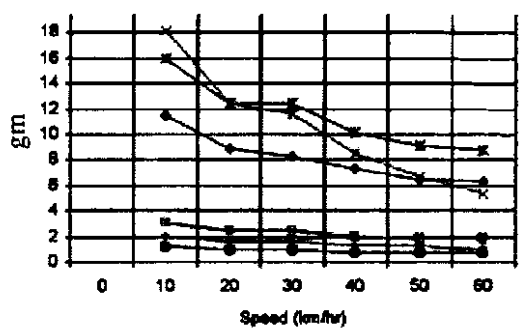
Speed	0 (km/hr)		10(km/hr)		20(km/hr)		30(km/hr)		40(km/hr)		50(km/hr)		60(km/hr)	
	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI
FC (gm/hr)	500	600	786.7	1146	1117	1783	1515.4	2674.5	1757.7	2923.3	2099.2	3277	2583	3775
FC (gm/km)			78.7	114.6	55.8	89.2	50.5	89.15	43.7	73.08	42.0	65.6	43.1	62.9
CO_2 (gm/hr)	1322.2	1697.	2080.	3240	2953	5040	4007	758.1	4647	8260	5548	9257	6824	10655
CO_2 (gm/km)			208.	323.9	148	252	133.6	252.7	116.2	206.49	111.0	185.1	113.7	177.6
CO (gm/hr)	12	15.5	19	30.5	27.1	48.1	36.8	72.6	42.7	80.32	51.8	92.2	65.6	110.3
CO (gm/km)			1.9	3.1	1.4	2.4	1.2	2.4	1.1	2.0	1.0	1.8	1.1	1.84
NO (gm/hr)	1004	1242.	1545	1824	2168.	2503	2903	3485	3054	3436	3180	3362	3223	3252
NO (gm/km)			154.5	182.4	108.4	125.1	96.8	116.2	76.3	85.9	63.6	67.2	53.7	54.2
SO_2 (gm/hr)	65.1	83.6	102.4	159.6	145.4	248.3	197.3	372.5	228.9	407.1	273.3	456.4	336.3	525.7
SO_2 (gm/km)			10.2	16	7.3	12.4	6.6	12.4	5.7	10.1	5.5	9.1	5.6	8.8
Soot (gm/hr)	5.8	6.9	9.1	13.2	12.9	20.6	17.5	30.9	20.3	33.7	24.2	37.8	29.8	43.6
Soot (gm/km)			0.8	1.24	0.6	0.96	0.5	0.96	0.5	0.79	0.45	0.71	0.46	0.68
PM (gm/hr)	9.1	10.9	14.2	20.7	20.2	32.3	27.4	48.4	31.8	52.9	38	59.3	46.7	68.3
PM (gm/km)			1.42	2.07	1.01	1.61	0.91	1.61	0.8	1.32	0.76	1.19	0.78	0.99

Figure 12: Fuel Consumption and Exhaust Emissions from Four-Wheeler Diesel (DI and IDI) Vehicles

Emissions per km for 4WD (DI) Vehicles



Emissions per km for 4WD (IDI) Vehicles



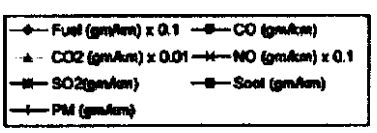
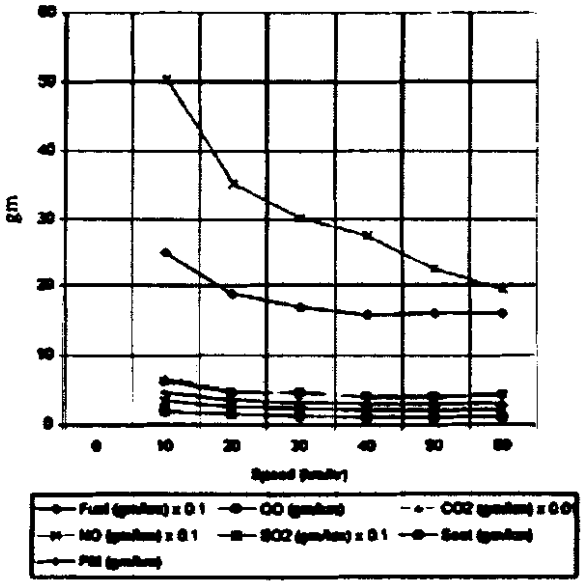


Table C5: Emissions from Buses/Trucks

Speed (km/hr)	0	10	20	30	40	50	60
FC (gm/hr)	1270	2522.6	3775.2	5027.8	6280.4	7931.1	9581.7
FC (gm/km)		252.3	188.8	167.6	157	158.6	159.7
CO_2 (gm/hr)	3359	6670.6	9982.3	13293.9	16605.6	20960.1	25314.3
CO_2 (gm/km)		667.1	499.1	443.1	415.1	419.2	421.9
CO (gm/hr)	30	60.6	91.2	121.8	152.4	197.5	242.6
CO (gm/km)		6.1	4.6	4.6	3.8	3.9	4
NO (gm/hr)	3048.4	5043	7037.7	9032.3	11027	11345.7	11665
NO (gm/km)		504.3	351.9	301.1	275.7	226.9	194.4
SO_2 (gm/hr)	16.5	32.9	49.2	65.5	81.8	103.3	124.8
SO_2 (gm/km)		3.2	2.5	2.2	2	2.1	2.1
Soot (gm/hr)	9.14	18.2	27.2	36.2	45.2	57.1	69
Soot (gm/km)		1.8	1.4	1.2	1.13	1.14	1.15
PM (gm/hr)	23.0	45.7	68.3	91.0	113.7	143.6	173.4
PM (gm/km)		4.6	3.4	3.0	2.8	2.9	2.9

Figure 13: Fuel Consumption and Exhaust Emissions from Heavy-Duty Diesel Vehicles

Emissions per km for Buses and Trucks



Appendix-D

Table D1: Emission Estimates (in Thousand Tons) from Seven Major Indian Cities for the Year 1997

	CO	CO_2	NO	HC	SO_2	PM	Soot
Delhi	386.78	5460	1520	177.77	91.07	18.82	7.53
Mumbai	153.54	820	310	30.85	19.24	5.02	2.01
Kolkata	114.91	550	440	12.31	26.79	5.54	2.21
Chennai	99.04	240	230	63.62	13.46	3.14	1.26
Bangalore	91.99	220	250	69.13	14.77	3.35	1.34
Hyderabad	44.23	630	130	50.51	8.16	2.20	0.88
Ahmedabad	39.53	580	140	37.59	8.634	2.03	0.81

Table D2: Average Service Life and Annual Distance (km) Traveled by Indian Vehicles

Vehicle	Life Years	Annual kms
2-Wheeler	15	10,000
3-Wheeler	10	40,000
Passenger car	20	15,000
Taxis	10	30,000
MUV	15	37,000
Trucks	15	40,000
Buses	8	30,000
LCV	5	60,000

MUV – Multi-Utility Vehicles; LCV – Light Commercial Vehicles

Source: Transport Fuel Quality for Year 2005, page 208, Central Pollution Control Board, New Delhi.

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The United States Agency for International Development's (USAID) energy and industry-related activities include promoting clean energy development, efficient energy use, and pollution reduction in key industries, especially with regard to greenhouse gases. USAID is strengthening incentives for adopting clean technology practices and certified environmental management systems that are climate friendly, thereby reducing greenhouse gas emissions. This report is an outcome of a continuing study supported by the USAID Office of Environment, Energy, and Enterprise in India.

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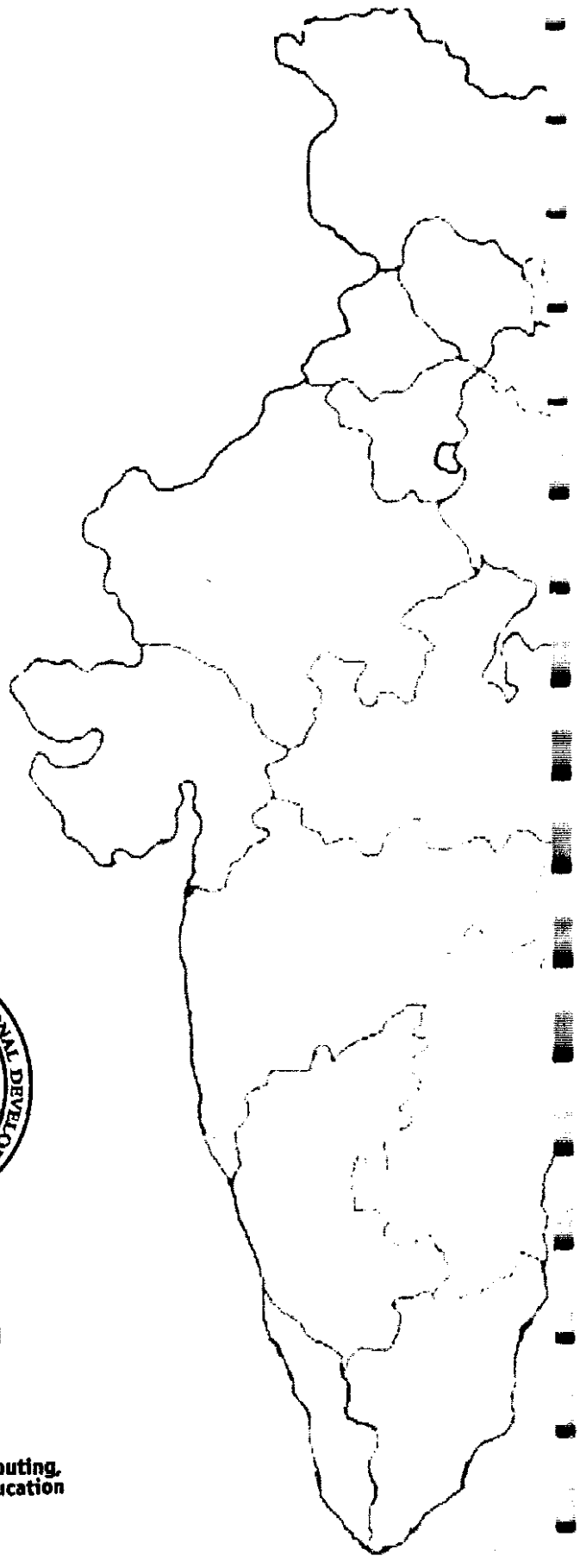


OSC

Innovations in computing, networking, and education

ANNEX B

FUEL TECHNOLOGY INTERVENTIONS

ANNEX B – FUEL TECHNOLOGY INTERVENTIONS

In India, fuel is distributed primarily by four large oil companies namely, Indian Oil Corporation, Bharat Petroleum, Hindustan Petroleum and Indo-Burma Petroleum. Recently Reliance Petroleum has produced one of the largest grass-root refineries in Asia. The quality of fuel to be supplied by all companies is monitored as per the specifications of Bureau of Indian Standards (BIS). These standards are revised periodically according to the requirements of evolving vehicle technologies and/or environmental requirements.

Implementation of some of the critical fuel parameters has been improved in the last few years in order to meet the requirements of better vehicle technologies that are being introduced in cities like Delhi, Mumbai, Chennai and Kolkata. The benefit of improved vehicle technologies in terms of reduction in emissions can be achieved only if the matching fuel is available. As a result of this, it is recommended that the sulfur content in both gasoline and diesel be reduced to 500 PPM in the above cities.

Conventionally automobiles are either Spark Ignition (SI) or Compression Ignition (CI) engines powered respectively by petrol and diesel. Alternative fuels like Liquid Petroleum Gas (LPG) and Compressed Natural Gas (CNG) are also being used in engines in some countries and movement in this direction has already been made in India. LPG is currently the most widely used alternate fuel with over four million vehicles running on LPG in the world.

The development of fuel technology begins with the combustion in the engines of which the automobile fuels provide the energy for propulsion. Besides providing energy, fuels must enable satisfactory vehicle performance in terms of cold/hot weather starting, trouble-free driving, power generation, fuel economy and reduced emission of pollutants. They also need to be compatible with the materials used in the engines and should not lead to excessive wear or cause deposits on the engine components. Auto fuels should also be safe to handle in terms of storage in vehicles and they should be able to be easily distributed through the marketing network.

Vehicular emissions are dictated by the combination of vehicle technology, auto-fuel quality, vehicle maintenance, driving patterns and various other factors. Therefore, any combination of engine technology and fuel that meets the prescribed vehicular emission norms is acceptable from environmental angle. Throughout the world, vehicular emission standards and the associated fuel quality necessary to meet these standards should be provided thereby giving a choice to the manufacturers, owners and operators of motor vehicles.

A. Improvements in Fuel Quality

The science of fuel technology is complex and the composition of fuels is such that as some elements are changed in order to achieve cleaner emissions then the effects from other elements may become worse. Improvement in fuels is thus largely the province of the central government and the fuel companies rather than the local states and cities. Nevertheless, the local authorities have a role to play in determining policy and making provision for easy and efficient distribution of the new fuels. As a result, refineries have implemented major programs for the upgrading of petrol and diesel quality in the past few years.

Lead is added to petroleum in order to increase the octane number and is still utilized in many developing countries today. The specification of lead in Indian petrol used to be a maximum of 0.56 grams/liter in 1994, but since February 2001 lead has been phased out and only unleaded petrol is produced and sold throughout the country. This places India in the forefront of controls in this particular aspect. In some developed countries, the lead phase out was spread over a period of ten to twenty years. China and many other countries in the Asia Pacific region and in Europe, South America and Africa have not yet phased out leaded gasoline.

- **Increasing the octane number in petroleum** - The octane number of petrol controls and signifies the level of performance of automobile engines. Increases in octane number were made effective 1st April, 2000. Removal of lead from petrol had originally reduced the octane number but with the installation of new facilities in refineries and changes in refinery operation, the octane number has since been increased. Premium grade petrol with an octane number of 93 is also supplied in major cities.

- **Reduction of sulfur content in petroleum,** - The sulfur content in petrol has been reduced by 50 percent, from a maximum of 0.20% to a maximum of 0.1%. Effective 1st April, 2000, the sulfur reduction requirement covers the entire country. In addition, the four largest metro areas are being supplied with petrol having a maximum sulfur content of 0.05%, which represents a reduction of 75 percent over other areas.

- **Introduction of benzene content limit into petroleum** - Until recently, there was no limit in the benzene content in India. This changed on 1st April, 2000, when a maximum of 3% benzene content by volume was introduced in the four metro cities and a maximum limit of 5% by volume was established for the rest of the country. It should be noted that the actual benzene content is substantially lower than the maximum specification. Some cities in India have gone even farther in reducing the benzene content. In the National Capitol Region comprising Delhi and surrounding satellite towns, and Mumbai, for example, the benzene limit has been reduced to a maximum of 1% by volume. In EU countries, by comparison, there was a maximum limit of 5% by volume until the beginning of the year 2000. Most of the countries in the Asia Pacific region, including China, along with South America and Africa do not have any specifications for benzene content, which places India in a admirable international position regarding the control of this particular pollutant.

- **Reduction of sulfur content in diesel** - The sulfur content in diesel was reduced by 75 percent, dropping from a maximum content level of 1% in 1996 to a maximum of 0.25%. This countrywide reduction occurred over a four year period from 1st April, 1996 to 1st January, 2000. In June 1997, the Government approved the establishing of nine Diesel Hydro De-sulfurization (DHDS) plants in nine refineries for the purpose of reducing the diesel sulfur content from the maximum of 1% to 0.25%. These plants have enabled the supply of diesel with a maximum sulfur content of 0.25% to be delivered throughout the entire country starting from 1st January, 2000. In addition, in the four metro cities, the sulfur content in diesel has been reduced by 95 percent to a maximum sulfur content level of 0.05%.

- **Increase in cetane number in diesel** - The cetane number in diesel signifies the ignition performance of the engine. A higher cetane number indicates better performance and lower pollutant emissions. Starting from April, 1, 2000, the cetane number was increased

from 45 to 48. This cetane number is very high compared with most of the countries in the world, where the cetane number varies between 40 and 51.

B. Candidate Fuels

Over recent years, the common fuels of gasoline and diesel have been gradually refined with the biggest improvements being the removal of lead from gasoline and the addition of catalytic converters. The increased consciousness of the adverse environmental and health effects caused by exhaust emissions has accelerated the search for cleaner burning fuels. The approaches tend to be either a completely new fuel technology or partial additions with other substances in order to reduce the harmful emissions. The principal candidates for the future are:

Liquefied Petroleum Gas [LPG] - LPG is used by many vehicles worldwide and is probably the most popular alternative fuel in use. Until recently, LPG was used mostly for domestic (cooking) purposes but the government has now approved this for use as an automotive fuel. The Safety Code of Practice is being drawn up and the specification for its use is under preparation. The most likely application will be in auto-rickshaws, although both taxis and passenger cars are also possible candidates.

LPG is an alternate fuel option employed by a large number of vehicles worldwide. Currently, worldwide, there are, in most probability, more vehicles operating on LPG than with natural gas. Vehicle manufacturers in India have started trials on newly developed LPG vehicles and its use is being considered for the transport sector, particularly in the metro cities, for auto-rickshaws, taxis and cars.

Like natural gas, LPG, comprising largely of propane, is a clean burning, low polluting engine fuel. It can be used as a substitute or as a sole fuel in place of diesel or gasoline. LPG can be used as a sole fuel in spark ignition (SI) engines fully replacing gasoline or as a supplementary fuel in compression ignition (CI) engines in a dual-fuel mode partly replacing diesel. In either case, the option of a switch back to gasoline or diesel operation is possible. LPG is propane liquefied for storage. A low cost fuel, it needs very specialized tanks, but leaves no deposit on vehicle parts and has an excellent safety record.

LPG fuel-system technology is well developed. Mostly the systems are mechanically based and are designed as 'Second Fuel Systems', to be added into gasoline fuel systems, for dual-fuel operation.

The exhaust emissions of unburned hydrocarbons for LPG vehicles are about the same as, or higher than, those of gasoline vehicles. This depends upon the interaction with the emission controls of the original gasoline fuel system. Carbon monoxide is normally lower, while oxidation of nitrogen shows no change. In diesel engines, nitrous oxides emission is lower at part-loads and higher at full load and is expected to be lower than diesel operation over the duty cycle of the engine.

Compressed Natural Gas [CNG] - Natural gas is generally incorporated with lower low cost and tends to be in abundant supply. Natural gas is found mostly as methane in the ground and is a growing market for propulsion fuels. It is clean burning and already plays a significant role as a motor fuel in many countries. When the fuel is used in engines which have been converted for such use, the combustion is more complete than gasoline and results in lower levels of GHG related emissions. More importantly, natural gas does not contain any benzene emissions or aromatic compounds, and when used in place of diesel, natural gas does not produce any particulate matter. Since natural gas has a higher octane rating than say, gasoline, engines will work at improved efficiency levels and will reduce carbon dioxide, the main greenhouse gas.

In India, it can be anticipated that the use of this fuel will increase rapidly. This is especially the case for auto-rickshaw operators since they can virtually halve their fuel costs by switching to CNG. Delhi paved the way and has proven that these vehicles can operate on CNG after conversions are made. It would be timely for this technology to expand to other cities.

Many commercial vehicle operators in India, and especially the owners/operators of three-wheel vehicles, can appreciate the value of natural gas as a plausible alternative because it is virtually less than half the price of petrol. Since natural gas three-wheelers are operating successfully in Delhi, the same can, and should be considered for other cities provided that the supply of CNG is assured. Vehicles running on petrol are most suitable for conversion to natural gas or dual mode, as no modifications are required on the existing engine.

Conversion costs for three-wheelers can range from around plus or minus Rs 15,000, provided that the vehicle is technically suitable for conversion. The cost of conversion of cars to CNG ranges from Rs 25,000 to Rs 35,000 depending upon the make of the vehicles. Heavy vehicles however, are generally not suitable for conversion. The cost of a new CNG vehicle depends upon the size and number of storage tanks that are fitted on the vehicle. Today there are several options for conversion available in India, including a system for smaller vehicles that can run on both gasoline and natural gas.

Alcohol Fuels - Ethanol has attracted considerable attention as a motor fuel over the years. Heavily promoted during the fuel crisis in the 1970s when gasoline was in short supply, ethanol can be produced from agricultural crops such as sugar or corn but is expensive to produce with current technology. It also requires large areas of land for the crop and large costs for harvesting. The future will, no doubt, provide better ways to harness this product. At the moment, however, it remains a fairly costly option. Blended with gasoline, ethanol forms a product called gasohol, and can be burned in ordinary spark ignition engines. India is already experimenting with 5% gasohol blends. Blends of 85% (E85) and 10% (E10) are the most common blends in other parts of the world. Flex fuel vehicles (FFVs) can operate with up to 85% ethanol.

Methanol, produced from natural gas, coal, bio-mass, needs compatible engine parts, and special engine oil, and is not as viable as Ethanol as an alternative fuel option.

Hydrogen - Hydrogen has the potential to be the cleanest-burning motor fuel. In the long term, and looking at the more extreme measures that might be necessary to reduce CO2 emissions and reduce the effects of global warming, the use of hydrogen fuel produced from renewable energy sources is a possible fuel option. Renewable energy sources provide the best solution to fuel security.

Hydrogen's potential for reducing exhaust emissions stems from the absence of carbon atoms in its molecular structure. Because of the absence of carbon, the only pollutant produced in the course of hydrogen combustion is NO_x. Hydrogen combustion also produces no direct emissions of CO_2. Indirect CO_2 emissions depend on the nature of the energy source used to produce the hydrogen.

Hydrogen, however, has properties that make it problematic to use in motor vehicles. Hydrogen has two main problems: production and storage. Hydrogen is not a fossil fuel, and is not found in significant quantities in nature. Therefore, it must be manufactured. Hydrogen can be produced by a number of methods, of which the most common are electrolysis of water, reforming natural gas, or partial oxidation and steam reforming of other fossil fuels. The most economical source of hydrogen is from reforming natural gas. Hydrogen is currently manufactured in limited quantities as an industrial chemical, as rocket fuel and in larger quantities for use in petroleum refineries and chemical plants. Electrolysis is sometimes used to produce high-purity hydrogen for special purposes but cannot compete economically with natural gas reforming for large-scale production. The potential future sources include electrolysis of water using large-scale, cheap photoelectric or solar-electric systems, or cheap abundant, and environmentally benign hydroelectric or nuclear-electric plants.

In the nearer term, renewable hydrogen could be produced from biomass. Hydrogen could also be produced on a large scale through in-situ gasification of coal, but this would result in large emissions of CO_2, as well as localized environmental damage due to subsidence and possible groundwater contamination.

The most promising approach to the use of hydrogen for vehicular propulsion is to react it with oxygen in a fuel cell to supply electric energy to a hybrid-electric vehicle. Fuel cells are extremely efficient compared with internal combustion engines and hydrogen-air fuel cells produce no pollutant emissions. Thus this system would be similar to a battery-electric propulsion system, except that the fuel cell and fuel supply would require significantly less weight and bulk than a battery system for the same energy storage. The fuel could be supplied and stored as hydrogen or could be produced on-board by the reformation of methanol, natural gas, or by the reaction of water with sponge iron. Producing hydrogen for the fuel cell by reforming hydrocarbon fuels may be especially attractive – both because of the increased ease of handling compared with pure hydrogen and because this approach could continue to use the fuel supply infrastructure already in place.

Research and development work on hydrogen-powered vehicles is progressing in a number of countries including the United States, Canada, Germany, and Japan. A number of companies including General Motors, Daimler/Chrysler, Honda, Toyota and Nissan have already introduced, or have plans to introduce, hydrogen fuel cell powered vehicles into their vehicle offerings. Another promising development is a prototype sixty passenger hydrogen bus produced by Canada's Ballard Power Systems, a leader in fuel cell technology. This proton-exchange-membrane (PEM) fuel-cell bus has been put in service in Vancouver, Canada and is capable of traveling at normal operating speeds and can travel more than 400 km on a single hydrogen

charge. The Ballard prototype, however, costs three times as much to operate as a comparable diesel bus. Economies of scale and improved fuel cells might make it competitive with conventional diesel buses beyond 2005.

Hydrogen has the potential to be the cleanest–burning motor fuel. With the virtual elimination of CO and HC exhaust emissions, only nitrogen oxide emissions would be present in any significant quantify in the vehicle exhausts. NO_x emissions from existing prototype hydrogen vehicles are similar to those from gasoline vehicles.

In order for hydrogen to become available as a motor fuel, significant investments would be needed in the infrastructure for the delivery, storage, and dispensing of the fuel.

In regards to storage, hydrogen can be stored on-board a vehicle as a compressed gas as a liquid, or in chemical storage tank in the form of metal hydrides. Hydrogen can also be manufactured on-board the vehicle by reforming natural gas, methanol, or other fuels, or by the reaction of water with sponge iron. In the latter case the sponge iron is oxidized and must be regenerated periodically. Compressed hydrogen occupies roughly 14 times the space of an equivalent amount of gasoline. Thus, compressed gas storage would add significant bulk and weight to a vehicle – about three times the bulk and weight of an equivalent volume of compressed natural gas. Vehicle range and refueling frequency would also be significant constraints.

Even as a liquid, however, hydrogen would still occupy roughly four times the volume of an equivalent amount of gasoline. Furthermore, the energy required for refrigeration to liquefy the hydrogen could easily exceed the energy value of the fuel itself, resulting in an extremely inefficient system.

The third option for hydrogen storage is in the form of metal hydrides. Current metal hydride storage systems are heavy and bulky, but less so than the storage cylinders required for compressed hydrogen. This is considered the leading technology for storing hydrogen for vehicular use. Research is under way in several countries to improve these characteristics, and some vehicle manufacturers in Germany and Japan are developing prototype vehicles.

The high cost of production, lack of storage reserves, and the large quantities required for hydrogen to be used as a motor fuel, are anticipated to be barriers to hydrogen as a cost-effective fuel in the near future.

Electricity - Electric-powered vehicles are often classified as having zero-emission qualities because there are no pollutants emitted from the vehicle itself. The pollutants are actually transferred to the power plants producing the electricity, although these are normally in remote locations out of town. The fact remains, however, that in terms of urban pollution emissions, the vehicles can be considered as pollution free. Vehicles powered in this way have been available for many years and continue to gain popularity and acceptance for use in areas where their silence and non-polluting qualities are at a premium. Delivery fleets, shuttles for airports, warehouse utility vehicles, resort transportation, park police transport and parking meter monitors are just a few of the niche markets where electric vehicles are currently employed and gaining ground.

Indian domestic companies have been developing such vehicles over the last few years and an auto-rickshaw is currently being tested. It is fair to say that the technology is acceptable and the need for commercialization should be further investigated. The special properties of electric vehicles make them ideal for sensitive areas such as city centers and tourist sites.

Fuel Cells - Further discussed under "hydrogen". Fuel cells have several advantages over batteries. First of all, the energy density can be increased by increasing the size of the fuel tank, since the specific weight of the fuel plus fuel tank are typically much less than the fuel cell itself. Secondly, fuel cells can be quickly 'recharged' by refilling the fuel tank. Because of the difficulty of on-board hydrogen storage, a large amount of work has proceeded to develop reformers to convert methanol or other liquid hydrocarbon fuels into H_2 and CO_2.

Phosphoric acid fuel cells (PAFC) are fairly well developed and are being demonstrated as part of a hybrid PAFC-battery electric power plant for a small bus. This is the only fuel cell technology which has demonstrated the ability to run on hydrogen from reformed hydrocarbon fuels for long periods without degradation. Disadvantages include: the use of noble metal catalysts; slow start-up; large volume; and weight. Proton exchange membrane (PEM) fuel cells require purer grades of hydrogen, which can poison the noble metal catalyst. Noble metal loadings are currently about 10 times higher than those required for PAFCs, which adds a significant cost to the cell. However, PEM fuel cells offer fast start up, rapid response, good power density relative to other fuel cells, long life, and good low-temperature performance.

Vegetable Fuels - Vegetable oils considered as possible substitutes for diesel fuel can be produced from a variety of sources including rape seed, sunflower, sesame, cotton, peanut, soy, coconut, and oil palm. Vegetable oils have been promoted as a possible replacement for diesel fuel because of their good ignition quality. The high viscosity of vegetable oils, however, results in poor fuel atomization, fuel injector blockage, ring sticking, and contamination of lubricating oil. This makes them best used as blends, in mixtures of up to 50%, with diesel fuels

When used in blends, vegetable oils produce higher emissions of CO, HC, and PM as compared to pure diesel fuels. Bio-diesel is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower viscosity fuel (oil ester) that is similar in physical characteristics to diesel. They can be used neat or blended with petroleum and diesel. Care must be taken to remove the glycerin residues produced as a by product. Engines running on neat bio-diesel or blended with petroleum diesel tend to have lower black smoke and CO emissions but higher NO_x and possible higher emissions of particulate matter. These differences are not large, however. Other advantages of bio-diesel include high cetane number, low viscosity, very low sulfur content, and the fact that it is a renewable resource. Disadvantages include high cost (US$0.39 – 0.91 per liter before tax) and reduced energy density (resulting in lower engine power output). The effects of bio-diesel on engine performance and emissions over a long period in actual service are not well documented.

Although the use of vegetable oils in diesel engines dates back to 1900, the modern use of bio-diesel fuel started in the early 1980's when vegetable oils – soybean oil, sunflower oil, corn oil, cottonseed oil, and rapeseed oil – were first used as experimental substitutes for diesel fuel in farm tractors. Interest in bio-diesel plunged along with the price of oil in 1983. Recently, interest in cleaner air and renewable energies has led to renewed private and public focus on bio-diesel fuel.

Owing to the high price of conventional diesel fuel in Europe (US$3 to US$4 per gallon), a sizeable number of diesel vehicles in Austria, Belgium, France, and Italy run on bio-diesel fuel made primarily from rape-seed oil. France is the world's largest producer of bio-diesel. Some of the advantages of bio-diesel are that the existing distribution system can be used, no new filling

stations needed, existing new engines can be used (but it is problematic to used bio-diesel on old engines), and that it will 'clean-out' the system.

Results from laboratory studies [see Alfuso and others 1993; Pagowski and others 1994; Scholl and Sorenson 1993; Tritthart and Zelenk 1990; Ziejewski, Gettler, and Pratt 1986] generally agree that blended or neat bio-diesel has the potential to reduce diesel CO emissions, smoke opacity, and HC emissions particularly poly-cyclic aromatic hydrocarbons. But these studies show an increase in NO_x emissions for bio-diesel fuel compared with diesel fuel at normal engine conditions. Generally there are lower particulate emissions especially under high-speed and moderately high-load conditions but a dramatic increase under low-speed and light-load conditions.

As for the HC emissions, research by School and Sorenson (1993) shows a reduction in HC emission when bio-diesel is used. There is some concern, however, that the organic acids and oxygenated compounds in bio-diesel may affect the response of the flame ionization detector, thus understating the actual HC emissions. Scholl and Sorenson also mention that the behavior of these compounds with respect to adsorption and non-absorption on the surfaces of the gas sampling system is unknown. There is controversy concerning effect of bio-diesel on particulate matter emissions. Alfuso and others (1993) report that some studies claim a reduction of particulate emissions when bio-diesel is used, while some studies show an increase.

The production of vegetable oil based bio-diesel fuel involves plowing the ground, planting, fertilizing, and harvesting the crops. This process requires the use of motorized farm equipment, which additionally produces exhaust emissions and use fossil energy. In addition, methanol or ethanol is needed in the process, and the emissions emitted to produce these compounds should be taken into account. In a life cycle study on rape seed oil and its esters, the German Federal Environmental Agency noted that other factors such as odor generated by fuel combustion and large emissions of nitrous oxide (N_2O) in the production cycle render the use of this fuel less attractive. Therefore the overall energy consumption and full fuel cycle emissions for bio-diesel fuel might be as high as those from conventional diesel fuel. Thus bio-diesel fuel might not be as attractive as other alternative fuels, such as natural gas, as a substitute for conventional diesel fuel.

The cost of bio-diesel fuel is one of the principal barriers making it less attractive as a substitute for diesel. The cost of vegetable oils in US is US$2-3 per gallon. The cost of converting vegetable oils to bio-diesel is approximately US$0.50 a gallon. Thus the total cost for bio-diesel fuel is US$2.50 – 3.50 per gallon. This is substantially higher than the cost of conventional diesel which is about US$0.75 – 0.85 per gallon. If waste vegetable oil is used, the cost of bio-diesel could be reduced to about US$1.50 per gallon. Since the heating value for bio-diesel is less than that for diesel, more fuel must be burned to provide the same work output as diesel. This adds further to the cost disadvantage of bio-diesel. Considering these limitations and the availability of less greenhouse gas intensive alternatives at similar cost in the US scenario, the use of rape-seed oil or its derivative is not easily justified from the standpoint of environmental protection. Where costs for vegetable oils and the conversion of the oils to bio-diesel can be substantially lower, however, this alternate fuel becomes more attractive, as it is in Europe.

ANNEX C

VEHICLE DESIGN INTERVENTIONS

ANNEX C – VEHICLE DESIGN INTERVENTIONS

The changes in fuel technology as noted Annex A will require appropriate and parallel changes to vehicle design in order to accommodate the new fuel supplied. In part, the new fuels will necessitate changes in the physical infrastructure and logistical systems to carry the fuel, but there also is a need for engine changes. These changes will either be made in the short term via the conversion of existing vehicles or in the longer term by the creation of new purpose built vehicles. In the early years, it was anticipated that carburetion will give way to fuel injection, engine management systems will be more and more prevalent and there will be higher compression ratios to give additional power for less fuel burning. The next steps will be to convert vehicles from petroleum and diesel to LPG or CNG. This is likely to be emphasized at first with the three-wheeler auto-rickshaw vehicles that are acknowledged as high polluting vehicles. In the more distant future, the fleet could change towards alternative fuels and hybrid vehicles. Other fuel options including bio-diesel, hydrogen fuel cells, electricity and alcohol may not be as economically feasible in the short term but could be viable within the second five year period leading up to the year 2010.

In parallel with fuel technology advances, various vehicle technology options should continue to be considered for Indian cities. Exactly what is considered "optimal" technology for vehicles is a relative concept, since, for example, cars running on solar cells have been used in Australia and the United States for many years, although not on a large commercial scale. Very efficient diesel engines using direct injection of fuel are now very popular in Europe. These engines reduce fuel use compared with ordinary diesel of the same power by as much as 30 %, although there are problems of NO_x emissions. Companies like Daimler, Chrysler and Ford are developing vehicles with fuel cells which do not have on-board combustion so there are no thermal losses. Some companies also advocate the use of battery based electric drives or a combined combustion/electric Hybrid. Companies like Mitsubishi, Honda and Nissan have a strong interest in direct injection gasoline engines that would reduce fuel use nearly to parity with diesel for the same (or better) performance.

A. Vehicle Technology Options

Based on the trends in fuel therefore, the following are options for vehicle changes that states and cities could incorporate into their twenty year Master Plans.

Auto-Rickshaws - Two and three wheelers form an important means of mobility within the Indian transportation sector. Together they comprise about 75% of the entire vehicle population; therefore the technological development in this sector in India is atypical compared with vehicular developments that have taken place in the other parts of the world. Various technology options for reducing exhaust emission from two and three wheelers are:

- Improvement in engine design for better scavenging and combustion
- Electronic engine management
- Advanced catalytic converters
- 4-Stroke petrol
- 2-Stroke direct injection

The technology mix will depend upon the each model of vehicle.

In India, two-wheeler technology is in an advanced stage and the emission norms being met by the present two-wheelers are among the most stringent in the world. Immense in-house research and development is required before the vehicles meet the next stage of emission norms and similar vehicle technology is not readily available world-wide. Indian manufacturers have indicated that the introduction dates for Stage III emission norms can only be reviewed once the stage II emission norms are well in place in the year 2005. Changes in engine technology along with matching fuel quality are expected to yield substantial benefits in terms of emission reduction. It is expected that these vehicles will proceed to the next level of emission controls using better fuel quality and technical efficiency. These changes alone will contribute to reductions in CO and CO_2 of approximately 40% and 50% respectively. After this initial fuel change, the conversion of the vehicles into CNG or LPG will generate reductions in emissions for CO (70% CNG or 40% LPG), for Hydrocarbons (63% or 50%) NOX (20% or 0%) and for CO_2 (42% or 15%). It can be seen that an appreciable change in harmful emissions will result from the advancements in fuel quality, efficiency and conversions.

Gasoline Passenger Cars - Gasoline powered vehicles in India were originally based on carburetor technology, with catalytic converter fitted passenger cars first introduced in 1995 in the four metro cities of Delhi, Mumbai, Chennai and Kolkata. Later in 1998, the move to catalytic converters was extended to 42 cities. Now, since only unleaded gasoline is available, all new passenger cars must have a catalytic converter fitted. Subsequently, and in order to meet the tight emission regulations, vehicle manufacturers started introducing gasoline fuel-injected engines with electronic engine management systems. The technology was further advanced and now passenger cars may have On-Board Diagnostics systems that continuously monitor the emission performance of the vehicle. The evolution of gasoline vehicle technology is given below:

- Carburetor engines
- Oxidation catalytic converter with open loop
- Exhaust Gas Re-circulation (EGR)
- Secondary air injection
- Throttle body /port injection
- 3-way catalytic converter with close loop
- Multipoint Fuel Injection System (MPFI)
- Electronic engine management
- On-Board Diagnostics (OBD)

Diesel Engine Cars (inc. Taxis) - The evolution of diesel engine technology has been in line with the changes in emission regulations. The emission regulation for diesel vehicles was introduced for the first time in 1992, one year after the introduction of emission norms for gasoline vehicles. Following are some of the technology changes that could be made or are being made to meet the next stage of emission norms.

- Oxidation Catalysts
- $DeNO_x$ Catalysts (Passive & Active)
- NO_x Trap Catalyst
- Optimum Fie +Comb. Chamber + Air Motion
- Turbo Charger (TC) + Variable Nozzle Turbine
- Selective Catalyst Reduction (SCR)

- Continuously Regenerating Trap (CRT)

Diesel Buses - The likely change here will be in the adoption of CNG as the fuel technology. This change will have reductions in CO of 16%, in NOX of 42%, in CO_2 of around 19% and in particulate matter by 98%.

Electric Vehicles - Electric vehicles are often classified as zero emission vehicles because no pollutants are emitted directly from the vehicle. This does not imply they are zero emissions overall, but only that the emissions are displaced from congested urban areas to remote locations. In the case of rechargeable batteries, this applies to power plant emissions. In case of fuel cells, commercial hydrogen production results in substantial and copious CO2 emissions.

Electric Passenger cars have been introduced in India by Mahindra & Mahindra, Bharat Heavy Electricals, Eddy Current Controls, and Cheetlec Vehicles. Bajaj Auto has also developed a 3-wheeler to run on electricity. The technologies developed so far have reached a level that meets the basic operational requirements of urban road transport and the industrial sector, and manufacturers are commercializing and marketing some of the various models developed.

The Government of India has shown an interest in supporting the development of battery operated vehicles in order to bring the vehicular emissions pollution under control and perhaps to anticipate uncertain access to oil at some point in the future. EVs have not yet, however, been successful in competing with other powered vehicles due to:

- Short range operation
- Poor road performance
- Need for regular long term charging
- Logistics for charging batteries
- High initial capital cost

The problem related to short range of current EVs is mainly due to non-availability of high-energy batteries with quick charging. The battery is thus an important factor for commercialization of EVs.

B. Vehicle Testing and Maintenance

At the present time in Indian cities, all vehicles are required to have a valid Pollution Under Control [PUC] certificate. These certificates are required to be obtained every six months, but many vehicles do not have the checks or perform the required maintenance. The Transport Department, SIAM, and the municipalities have identified the inherent weaknesses in a manual inspection system as contributor factors to the effectiveness of a testing and maintenance program. In response, some cities have recognized and are addressing the need for establishing a comprehensive data bank so that periodic monitoring of vehicles may take place. Research has showed that an effective PUC system will prove the most cost effective way to control pollution. If this is established and if periodic checking is enforced, the benefits will be a significant reduction in harmful exhaust emissions.

As a first step in this effort, it should be recognized that older vehicles pollute more than new ones. As a result some major gains would be made by encouraging the phasing out older vehicles and modernizing the fleet. In Delhi, for example, vehicles older than fifteen years are gradually

being removed from the roads. Even simple maintenance such as tuning and carburetor adjusting can provide pollutant reductions of up to 60%.

With PUC being the only current method of emission checking, it was recommended that improvements be made to the PUC Centers. Among the best practice recommendations which are currently being implemented in Hyderabad, the centers are being networked and computerized, 4-gas instead of 2 gas analyzers are being introduced, and standardized operating procedures are being developed and applied. It is important for the success for the pollution under control program that the PUC center personnel should be thoroughly trained in the SOPs to ensure consistency and accurate measurements. The recently completed GEP-CCS study has recommended that new PUC Centers should contain a digital camera for capturing the vehicle registration data and a computer to record all details of the tests carried out. The computer will then be able to produce the proper certification for the particular vehicle as tested. The installation of the computer will also enable the future linking of test centers and hence the creation of a data base.

In this way, the cities will be able to make major improvements to the overall fleet quality and will be able to reduce the greenhouse gas emissions from poorly maintained vehicles.

ANNEX D

UNITED STATES CASE STUDIES

ANNEX D - UNITED STATES CASE STUDIES

The United States has long been a pioneer in the use of advanced transportation planning and traffic engineering techniques for increasing efficiency in travel. In addition, recent work has concentrated on adapting these similar techniques to the benefit of the physical environment. These approaches have used similar techniques to those employed in the demonstration project in the City of Hyderabad as a lead in to this greenhouse gas emissions project.

IVHS (Intelligent Vehicle Highway Systems) - the Federal program designed to adapt electronic concepts to aid motoring is well established and is bearing fruit. These programmes have used electronic methods to improve items such as transit planning and ensuring that the systems are made more user friendly so as to attract passengers away from passenger cars to transit systems. Other examples of IVHS benefits in the field of environmental changes are in route planning via on-board computers and integrated signal systems triggered via on-bus transponders giving priority to these vehicles.

Below are some further examples of innovations aimed at enhancing public transit and reducing pollution from vehicles:

Bus Rapid Transit

The Federal Transit Administration (FTA) has launched a Bus Rapid Transit Demonstration Program supporting projects aimed a demonstrations of Bus Rapid Transit in selected cities across the United States. The program aims to adapt the principles of highly successful systems, such as those of Curitiba, Brazil, Lyon, France and Nagoya, Japan, to U.S. conditions, laws, and institutions. A primary goal of the program is to assess the demonstration projects through scientific evaluation.

There are several key concepts involved in making ordinary bus service into Bus Rapid Transit. Each concept can be realized by taking advantage of one or more BRT features.

Reducing Travel Time

All BRT projects seek to improve service by reducing travel time. The components of travel time include time getting to and from the transit stop, time waiting for the transit vehicle, and time in the vehicle. If a transfer is needed, there is also additional walking and waiting time.

A central concept in BRT planning is to give priority to transit vehicles, since on average they carry many more people than other road vehicles, and the goal should be to maximize person-throughput, not necessarily vehicle-throughput. One form of priority is to run service on exclusive rights-of-way such as busways and exclusive lanes on expressways. These techniques can greatly reduce in-vehicle travel time.

Another form of priority is to designate bus lanes on arterial streets. Providing traffic signal priority to transit vehicles can also speed operation on streets. Reducing the number of stops, providing limited-stop service, or relocating stops to areas where there is less congestion can also speed service, although potentially with the disadvantage of increasing walk time.

All of these techniques not only reduce in-vehicle time but by improving the reliability of service can reducing waiting time also. Since customers particularly do not like to wait for transit, reductions in waiting time can make service much more attractive. Automatic vehicle location systems can be used to manage bus service to regularize the intervals between buses, thereby minimizing passenger waiting time.

Changing fare collection policies to reduce or eliminate on-vehicle fare purchase can speed boarding. Using vehicle designs that feature fewer steps and more or wider doors can also reduce dwell time.

User Friendly Service

Although faster travel is a key element in improving service and attracting more transit trips, transit will not be attractive to many potential riders unless it is more user-friendly. Better passenger information can make transit service easier to use. Providing real-time bus status information (a by-product of automatic vehicle location) can reduce customer anxiety while waiting. A unified system design, with colors and images coordinated between stops, vehicles, and print materials, can simplify the experience of using public transit.
Using marketing techniques can make the public aware of service improvements, and also help to improve the public image of buses.

Making land use policy more oriented to developing and maintaining pedestrian-friendly areas will improve enhance the attractiveness of transit. In the long-run, land use policy coordinated with transit investments will help to make transit trips convenient by locating attractors conveniently adjacent to transit corridors and stations.

BRT Benefits

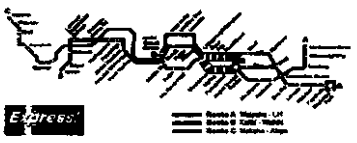
Reducing travel time will provide a benefit to all users of transit. In addition, faster service, combined with better information and better marketing to improve transit's image, will increase transit ridership. BRT can also help in the effort to promote transit-oriented land development. Understanding BRT features provides transportation planners the ability to offer a new transit option to the public which combines the ease-of-use of some rail service with the flexibility of bus service.

Case Study 1 below which highlights a 50km bus rapid transit system developed in Hawaii designed to carry 46,000 passengers a day to 31 stops between downtown Honolulu, Pearl Harbor, the University of Hawaii and area beaches. The project will serve 9,000 low-income households within a half-mile of the stops, and will reduce air pollutants by more than a third. More than 50% of the island's population and 80% of the island's jobs are located along the transit route.

CASE STUDY 1 - CITY AND COUNTY OF HONOLULU BUS RAPID TRANSIT (BRT) PROJECT

Project Description

The City and County of Honolulu has three routes in place in its Bus Rapid Transit (BRT) program. This started with the introduction of its first limited-stop fixed route service in March 1999, when CityExpress! (Route A) began operating along the 6.6 mile primary urban corridor between the Kalihi Transit Center and the University of Hawaii. The CityExpress! service expanded in August 1999 an additional 6.0 miles to the major retail area of Pearlridge Center.



This expansion provided limited-stop service along the primary urban corridor, where slightly more than forty percent of the population of Honolulu reside. In June 2000, service was extended to Waipahu with a terminus at the future site of the Waipahu Transit Center on Hikimoe Street.

On May 7, 2000, the City introduced CountryExpress! (Route C) to provide limited-stop service between the Waianae Coast to downtown Honolulu. CountryExpress! provides travel options for residents of the Waianae Coast through linkages to express, local, and circulator services from strategically located transit centers. In conjunction with the introduction of CountryExpress!, the City converted Leeward Oahu to a hub-and-spoke bus operation that significantly improved the efficiency of the service.

In August 2000, CityExpress! (Route B) began limited-stop service between Kalihi and Waikiki. This service was an overlay service along one of the busiest transit routes on Oahu.

CityExpress! (Route A) Overview

CityExpress! is a limited-stop bus service that links major destinations along the primary urban corridor between the community of Waipahu and the University of Hawaii. This 18.6 mile corridor links major residential areas, major shopping centers, government centers, the central business district, the convention center and the university.

Phase I of CityExpress! began on March 8, 1999 with a 6.6 mile service between the Kalihi Transit Center and the University of Hawaii in Manoa. The travel time was reduced from sixty-eight minutes on the local bus service to thirty-five minutes. The service operated from 5:30 a.m. to 10:30 p.m. seven days a week. Headways during the week were fifteen minutes and thirty minutes on Sundays and holidays. Nine standard forty-foot buses were used in the service. The buses were all wheelchair accessible and equipped with bike racks capable of carrying two bicycles. All CityExpress! bus stops were

clearly identified with special CityExpress! placards matching the CityExpress! "colors" displayed on the buses. Additionally, each CityExpress! bus stop was equipped with a "spinner" containing the route map and additional information on the CityExpress! system. Average weekday ridership in Phase I grew from an initial 2,200 to over 3,500.

Phase II of CityExpress! started on August 23, 1999, with an extension from the Kalihi Transit Center to the Pearlridge Shopping Center. This six-mile extension operated on fifteen to twenty minute headways on weekdays and thirty minute headways on Saturdays. The original 6.6 mile portion of the route was improved to 7.5 minutes in peak and 10 minutes base headways on weekdays. An additional six transit buses were added to the CityExpress! service for Phase II. The average daily ridership in Phase II increased significantly from around 3,500 in Phase I to over 6,000 in Phase II.

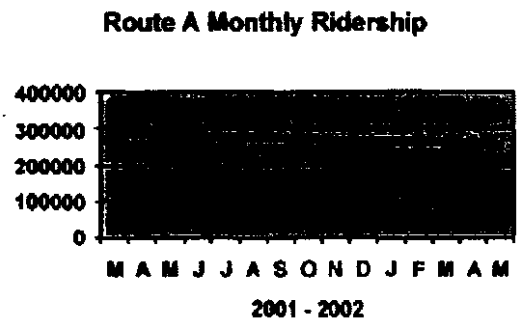
The expansion of CityExpress! continued in June 2000, with the seven mile extension from Pearlridge to the community of Waipahu. This extension operated along Kamehameha Highway and Farrington Highway before traveling on the H-1 Freeway to the Kalihi Transit Center and continuing to the University of Hawaii. The service operated on fifteen to twenty minute headways and provided the first direct link between Waipahu and the University of Hawaii. Sunday service was added at this time.

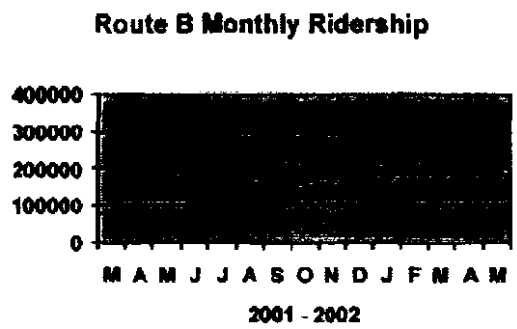
A new limited-stop service, CountryExpress! Route C, started on Sunday, May 7, 2000. The service operates from the Waianae Coast to the second city of Kapolei and to downtown Honolulu. CountryExpress! is a seven-day a week operation with thirty minute headways. The service runs from 5:00 a.m. to 10:00 p.m. daily. CountryExpress! saw the introduction of the City's new sixty-foot articulated buses. Ten articulated buses are used in the service.

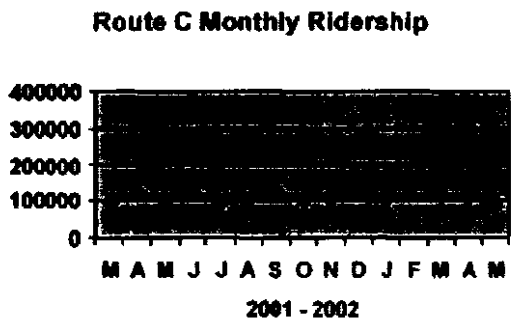
The introduction of CountryExpress! Route C was part of the City's conversion of Leeward Oahu to a hub-and-spoke bus operation. The conversion resulted in establishing ten community circulators, with unique three digit numbers, four new transit centers and modifications to all existing service. CountryExpress! is the focal point of the service providing linkage between the transit centers before transiting to Ala Moana Center.

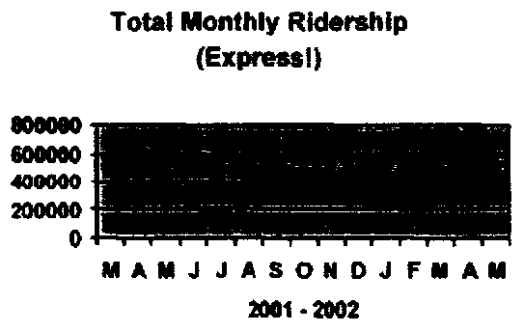
The success of CityExpress! Route A resulted in establishing CityExpress! Route B in August 2000. This service operates along and is additive to the Route 2 corridor that experiences over 50,000 boardings daily. The seven mile corridor is between the Kalihi Transit Center and Waikiki along School Street, King Street, Beretania Street and Kuhio Avenue. Route B operates on fifteen minute headways using forty-foot buses.

Express! Ridership





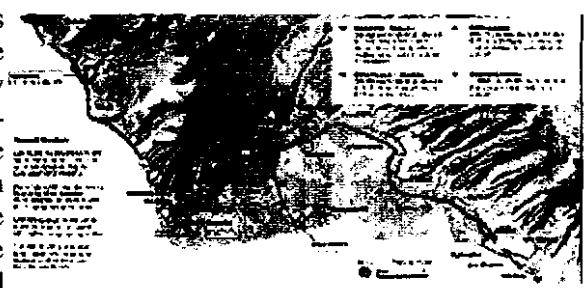




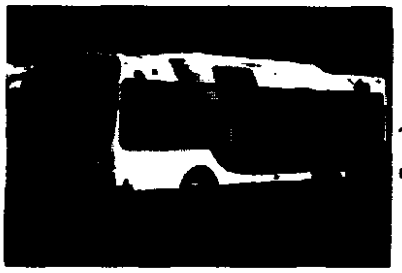
The ridership on all the Express! routes remains strong. Ridership was influenced by the terrorist attacks on September 11, 2001 and the resulting downward trend in the local economy. As the economy improves, ridership on the Express! routes will continue to increase.

Hub-and-Spoke Conversion

The City is continuing its efforts to convert from a radial bus route system to a hub-and-spoke system to improve operating efficiency.



The initial conversion of Leeward Oahu was completed and activated in August 2000. The Leeward conversion added ten community circulator routes designed to provide intra-community movement and a direct link to the transit centers in Waianae, Kapolei, Ewa Beach and Waipahu. At these transit centers, the community circulators are pulsed to arrive within minutes of the Route A and Route C, and the local routes to allow for direct transfers. The first "owl" service was implemented as part of the Leeward Conversion, with Route 40 running 24/7 between Waikiki and Ewa Beach.



The City introduced its new 30-foot Opus Buses, with a new color scheme, for the Community Circulator Routes.

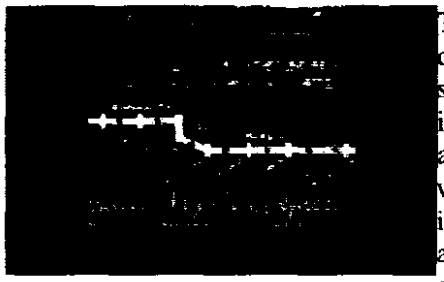
Phase II, the conversion of Central Oahu, started in March 2001. The conversion planning focused heavily on community input. Multiple community meetings were held to obtain the views of the residents regarding the type of transit service they desire. Focus group meetings were held with bus operators to receive their recommendations and observations. Ridership surveys were also conducted and help determine existing ridership patterns within the area. The Central Oahu planning is complete and will be phased into service after the construction of the transit centers in Mililani and Wahiawa.

Transit Centers

Transit Centers for Leeward Oahu are in the final design stages for Waianae, Kapolei and Waipahu, along with a transit hub in Ewa Beach. Construction of the Kapolei Transit Center will start September 2002. The hub-and-spoke project in Central Oahu identified sites for transit centers in Mililani and Wahiawa.

The designs for these transit centers are undergoing final design reviews. Funding for construction of these transit centers was approved in the Fiscal Year 2003 budget. The Mililani Transit Center (see rendering) will be constructed adjacent to the Mililani Town Center under a Memorandum of Understanding (MOU) between the City and the developer. This transit center will provide excellent transfer opportunities for passengers and an enhancement to the adjacent retail establishments.

Traveler Information Systems



The City, in partnership with the University of Hawaii, developed an internet-protocol based traveler information system that was tested on CityExpress! Route B. The information system was accessible on personal computers at cityexpress.Hawaii.edu. Electronic Route B route signs with LED displays that track the next approaching bus to inform waiting riders when the next Route B bus would arrive. This demonstration project showed that the community desired real-time information. As a result of the demonstration project, the City procured an electronic traveler information system that will be deployed after the installation of the new bus radio system in late 2002.

Signal Prioritization

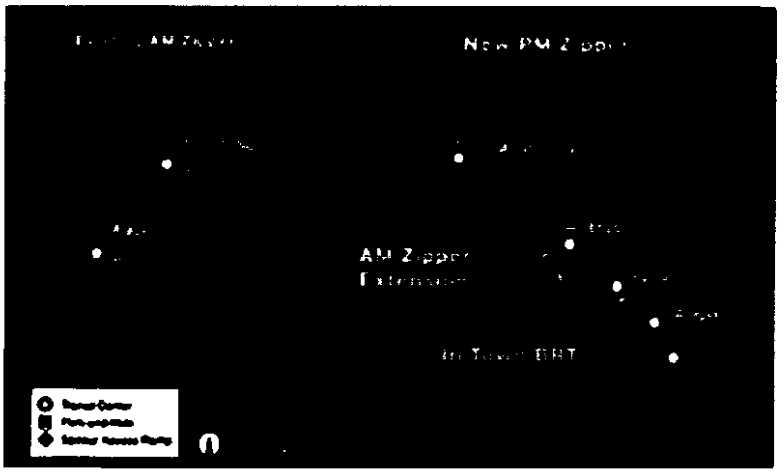
The signal prioritization program will result in all limited-stop buses having the capability to extend the "green" time at major intersections along the routes. The system will not allow the operators to change the signal from red to green but will allow the operators to extend the green time if the signal is green as they approach the intersection. The City is exploring a "corridor signal prioritization system" that will enable longer green lights at all intersection along the Express" corridors, except at major intersections. Installing signal prioritization at major intersections does not appear needed as the Express! buses stop before the intersection, limiting the need for increased green time.

All Door Boarding and Advance Fare Payment

Reducing dwell time through all door boardings is part of the City's plans. The initial step in achieving all door boarding, however, is to implement fare payment via smart card technology. The City recently awarded a contract to Booz Allen Hamilton to develop the specifications for a smart card system for the transit system. The consultant will also write the request for proposals for the system and assist the City in evaluating the proposals. Funding is provided in the Fiscal Year 2003 Capital Improvement Budget (CIP) for purchasing the system.

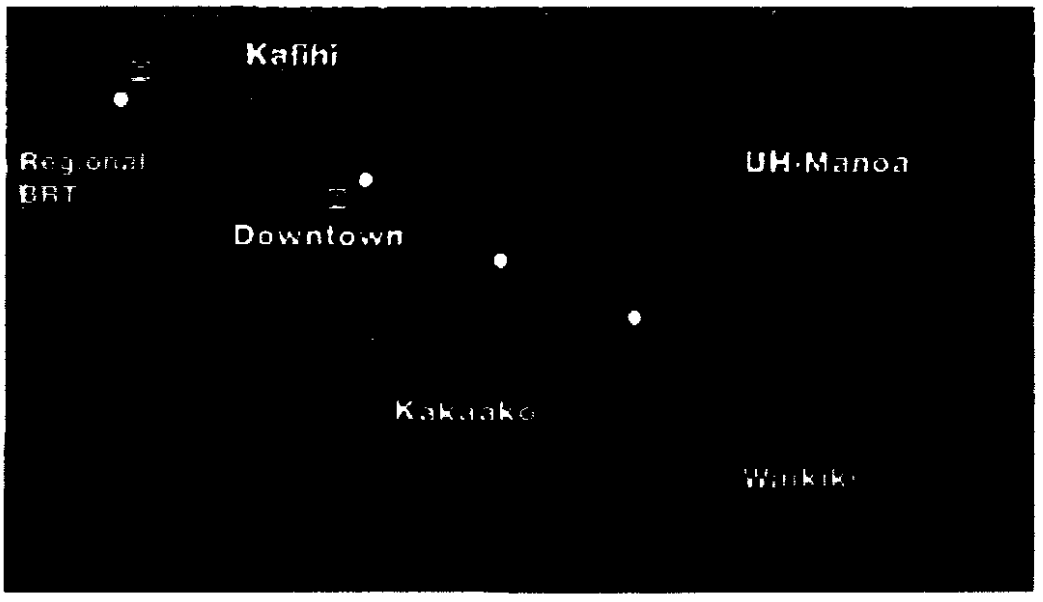
Regional BRT System

The City released its Supplemental Draft Environmental Impact Statement (DEIS) on March 13, 2002. This is an important step in the planning process for the Regional and In-Town BRT system for Honolulu. The Regional BRT will operate from Kapolei to the Middle Street Transit Center where it connects with the In-town BRT with branches to the University of Hawaii-Manoa, Kakaako and Waikiki.



In-town BRT System

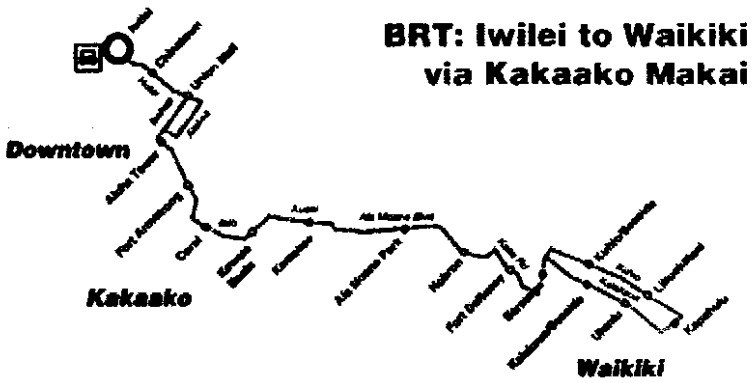
The In-town BRT will operate along a 12.8 mile corridor between the Middle Street Transit Center and the University of Hawaii-Manoa, with segments serving Kakaako and Waikiki. BRT service will provide fast and frequent service through the downtown area with major stops at the future Iwilei Transit Center, the Alapai Express Bus Terminal and Civic Center Complex, the Ala Moana Shopping Center and Waikiki. The peak hour frequency will be 2-4 minutes.



BRT-Phase I

Phase I of Honolulu's BRT system is becoming a reality. The City Council approved the funding in the Fiscal Year 2003 budget for implementing the Iwilei to Waikiki segment of the BRT system. This phase is planned to be operating within three years. Phase I will operate from the future Iwilei Transit Center to Waikiki, serving stops throughout downtown Honolulu, the Kakaako waterfront area, and Waikiki. Included in the budget is funding to purchase the land

adjacent to the existing Middle Street bus facility to establish a paratransit facility and the Middle Street Transit Center. The City is currently considering alternatives for vehicles to operate in the Phase I BRT segment.



Conclusion

The City is working hard to make transit fast, reliable, comfortable, and convenient ... so that transit becomes the travel mode of choice for Honolulu's residents and visitors.

It is clear that all of these approaches and views support a general move towards the shifting of travel away from individual private cars to a collective public transport system.

Light Rail Transit

In the 1970s American urban planners started to look to Europe for ideas on how to save their cities from sprawl and economic decline. With transportation companies now in public ownership, the introduction of better public transport could be achieved using a mix of city, state and national funding. At the same time, with the end of the Vietnam War, defense contractors were looking for alternative markets, and saw transportation as a growth area. This led to a decision by the surviving tramway cities of Boston and San Francisco to place orders with Boeing-Vertol for new articulated light rail vehicles to replace their PCCs, using a design that was intended to become the standard US LRV in the same way that the PCC had achieved standardization 40 years earlier. Unfortunately the resulting product was an expensive technical disaster, as Boeing tried to reinvent the wheel rather than learning from transit vehicle experience elsewhere.

The success of these systems in attracting back to public transit motorists who would not dream of using a bus led to a boom in the development and construction of light rail systems which is still going on. Baltimore, Buffalo, Dallas, Denver, Los Angeles, Portland (with America's first low-floor trams), Sacramento, and St Louis are all cities which have built new light rail lines, and many are continuing to expand. New systems are under construction in Jersey City and Salt Lake City, with planning in progress in other cities such as New York and Seattle. The systems at Cleveland, Pittsburg, Philadelphia and Toronto, which survived from the earlier streetcar era, have all acquired new rolling stock, and are extending again.

Case Study 2 below highlights Sacramento's light rail transit (LRT) system is a model of success for many smaller American cities.

CASE STUDY 2 - SACRAMENTO'S LIGHT RAIL: SUCCESS IN A SMALL CITY

Sacramento's light rail transit (LRT) system is a model of success for many smaller American cities considering LRT, such as Louisville, KY and Austin, TX. Operated by Sacramento's Regional Transit District (RT), the LRT system opened for service on 12 March 1987 with an 18.3-mile line (now expanded to 20.6 miles) linking the city's eastern and northeastern suburbs with downtown Sacramento.

A Model of Cost Containment

In its initial installation, Sacramento's LRT system was also a model of cost-saving efficiencies. It was constructed at a cost of $176 million in 1987 (including the cost of vehicles and maintenance/storage facilities). In year 2000 dollars, that would amount to about $228 million -- or about $12.4 million per mile. Costs were kept low by minimizing heavy civil works and using lots of single-track sections with passing sidings to enable 2-way train movements. (Gradually the line is being completely double-tracked as ridership volumes and public approval has grown.)

Also helping to keep costs low were the use of slightly over 7 miles of railroad right-of-way (ROW) and the re-allocation of ROW and even partially built structures of an abandoned Interstate freeway project (I-80), amounting to about 4.5 miles. Just under 5 miles of the line was built in city streets; that, and a small amount of bridgework and aerial construction, were the most expensive elements of construction in the original system.
Transit ridership nearly doubles

Today, RT's LRT system carries almost 30,000 passengers on a typical weekday. During Fiscal Year 1999, RT light rail vehicles carried 8.5 million passengers (about 30% of the agency's total ridership). [Source: Sacramento RT website 00/02/22]

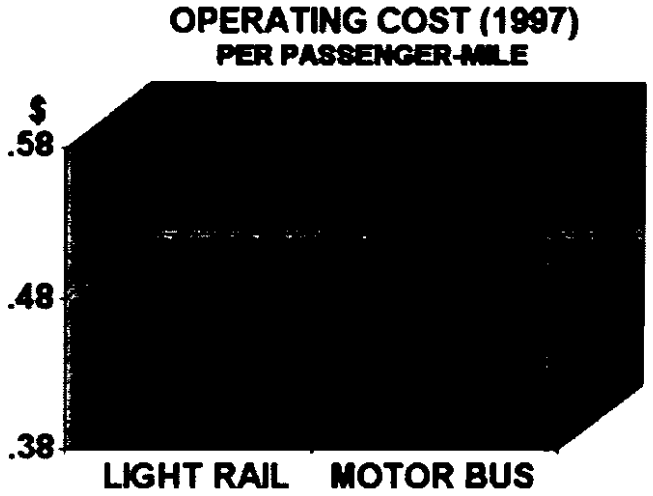
Put another way: Sacramento's LRT is carrying 30% of the city's transit ridership on 1.4% of transit routes, with less than 1% of the total passenger stops, and about 17% of total transit vehicles.

Annual ridership has steadily increased, on both the bus and light rail systems, from 14 million passengers in 1987 to almost 27 million passengers in FY 1999 -- possibly reflecting a positive impact by LRT on the attractiveness of the entire transit system, with its 418-square-mile service area. Bus weekday ridership reached an average of 66,000 passengers per day in 1999.

Ridership on LRT is ridership is up more than 50% since 1990 alone, and LRT seems to be particularly attractive to somewhat more affluent suburbanites who are traditionally wedded to travel by car. A study of the 1990 census published by the Transportation Research Board of the National Academy of Sciences reported that light rail ridership in Sacramento's suburbs was 60 to 70 percent higher than on equivalent bus service.

The LRT system was originally projected to serve 26,000 daily riders by this year. However, it actually hit that goal in 1996 -- 4 years ahead of schedule -- according to Mike Wiley, RT's

director of customer services. Furthermore, riders during non-commute hours account for 60% of the passengers -- a sign that people aren't just using the light rail for work, but are being attracted to LRT for shopping, recreational, and other types of trips.

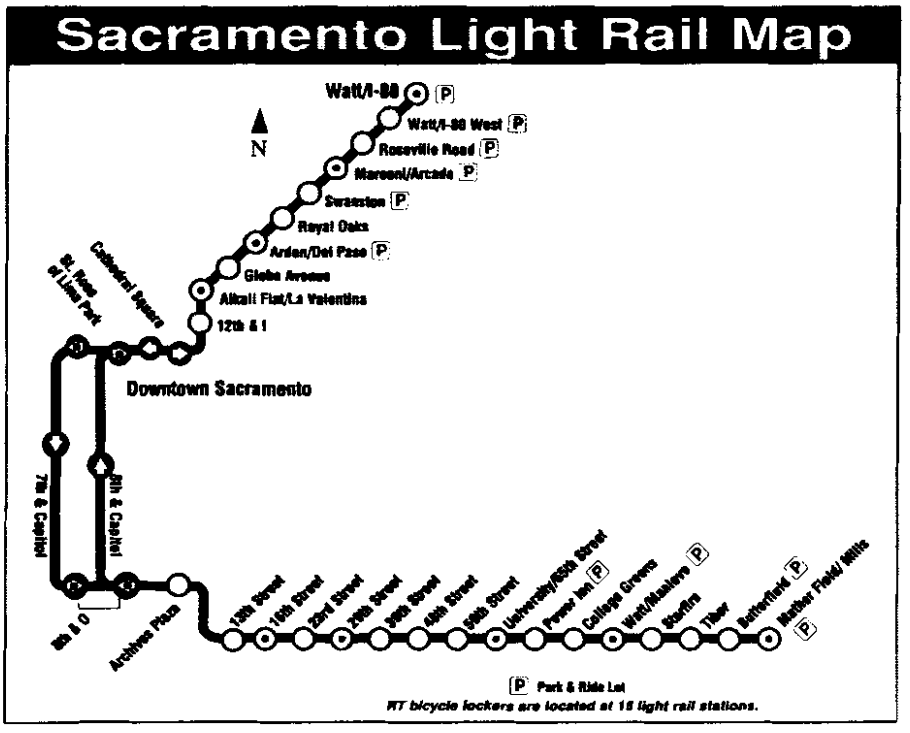


Besides attracting higher ridership - especially from automobiles - and helping invigorate the city's entire transit system, LRT has helped lower ongoing operating costs, compared to bus services. As the graph above indicates, Sacramento's LRT (as of 1997) was carrying riders for 38 cents per passenger-mile, compared to 56 cents by bus.
Impressive level of service

By reducing operating costs and attracting ever-higher ridership, LRT has enabled the operating agency to improve transit service at affordable cost.

Buses and light rail run 365 days a year. The LRT system operates 36 light rail vehicles, while the bus service runs 136 buses powered by compressed natural gas (CNG) and 73 diesel buses. Buses operate daily from 5 AM to 11:30 PM, every 15 to 60 minutes, depending on route. Light rail trains operate from 4:30 AM to 1 AM daily, with service every 15 minutes during the day and 30 minutes in the evening.

There are 31 light rail stops or stations, 9 bus and light rail transfer centers, and 10 free park-and-ride lots, in addition to over 3,500 bus stops throughout Sacramento County.



The LRT system currently includes 36 of track. Light rail trains traveled 950,000 miles, providing 45.1 million passenger-miles in Fiscal Year 1999. RT operates light rail trains seven days a week with eight trains running at 15-minute intervals during the day, and four trains running at 30-minute intervals during the evening and early weekend mornings. RT operates four-car trains during the peak periods and two-car trains during the off-peak hours. Single-car trains provide late evening and Sunday service.

The Siemens Duewag U2A vehicles currently used are 79' 6" long and 8' 9" wide, with 60 seats. Normal, comfortable loading will accommodate an additional 65 standing passengers, although higher numbers could be carried. The cars have a maximum speed of 55 mph. With the end-to-end running time on the light rail system at 55 minutes, the average schedule speed (with station stops) is 22.5 mph.

Even with surface operation, interface with other traffic has been smooth. Most private right-of-way, including all single-track sections, includes three-aspect (red, yellow, green) automatic signaling. Light rail operators use "line of sight" when operating on city streets and in low speed double track sections. That "low-tech" method of train control (as opposed to automatic train signals) has helped keep capital costs affordable. Most grade crossings are protected by standard railroad crossing gates.

RT uses a proof-of-payment fare structure throughout the system, meaning that passengers buy their tickets at self-service machines (or elsewhere), and must produce their ticket if asked to do so. Fare inspection officers conduct random train and station checks to verify fare payment. Passengers found without proof of fare payment are issued a citation, which carries a fine between $56 and $250. Light rail generated $6.3 million in fares, and operating costs totaled approximately $17 million in FY 1999.

All 31 stations, except the 12th & I inbound station, have Senior/Disabled platforms accessed by ramps or lifts. Thirteen stations offer bus transfer services and ten stations have free park-and-ride lots with 4,020 parking spaces. Each station is equipped with at least one fare vending machine/ticket validator and one bill change machine. All stations have telephones and most have lighted shelters.

Success Leads to Expansion

Air-quality issues have also convinced Sacramento decision-makers to expand the light-rail system while slowing slightly the growth of highways. A long-term regional transportation plan allocates 14% of $4.4 billion in proposed transportation system capital costs to light rail, though officials acknowledge that only 1% of daily trips will be by transit and 92% will be by car by 2022. Apparently, it's recognized that LRT has a substantial impact on peak-period trips into Sacramento's core area -- a small proportion of the total, but a heavy contributor to central-city smog problems. Also, automobile trip numbers are bloated by the vast quantity of short or "wasteful" trips (e.g., to convenience stores, gas stations, car washes, etc.) which transit users don't tend to make (especially if concentrations of activity centers, like retail outlets and malls, are located adjacent to some transit stations).

Because of its success, major extensions to Sacramento's LRT system are under way. These include a 10.2-mile extension to the suburban community of Folsom, a 0.7-mile extension to the city's downtown Amtrak station, and a 6.3-mile South Line extension to Meadowview Road. All three extensions are scheduled to begin operating by September 2003.