Journal of Atmospheric Pollution, 2016, Vol. 4, No. 1, 1-14
Available online at http://pubs.sciepub.com/jap/4/1/1

DOI:10.12691/jap-4-1-1

An Integrated Vehicular Emission Control Programme for the City of Delhi Using Retrofitted Emission Control Technologies

R.Gopalaswami*

Formerly Chairman & Managing Director, Bharat Dynamics Ltd Hyderabad, India
*Corresponding author: gopalaswami@gmail.com

Abstract The City of Delhi, with a human population of over 16 million has nearly 9 million vehicles on its roads running over 100 billion kilometers every year, spewing out nearly 4 million tonnes of fuel emissions into the atmosphere every year (9900 tonnes per day). About 2 to 5% of these emissions (about 200 to 500 tonnes per day) are in the form of highly toxic gases and particulate matter hazardous to human health and well being. This does not include tyre wear out on Delhi roads which further adds nearly 6000 tonnes of rubber per year (about 16 tonnes per day!) into that contributes greatly to hazardous, dense, black carbon particles that tend to remain near the ground causing serious respiratory and heart diseases. Delhi is now characterized as among the world's most polluted city. Analysis of 24x7 annual trend (for the year 2015) of multiple factors resulting in air pollution in Delhi indicates that it seems unlikely that traffic volume reduction alone will have a very significant impact on reducing air pollution especially in winter months. The problem of air pollution needs to be addressed retroactively at its technological root viz. the combustion process in internal combustion engines. Nearly 70% of air pollution in the City is due to vehicle emissions; the rest being from thermal power stations, industries, and open fires in winter. This paper recommends a comprehensive, sustainable and very affordable Vehicular Emission Control Regime, which will be a large technical challenge requiring a systems-based approach to address emission emitting vehicles. Fourteen enabling new and advanced technologies are identified for immediate test, evaluation, and deployment where found suitable based on a prioritized assessment of each vehicle's need. Several of these advanced technologies have already been fully developed and extensively certified in India in civil R&D. A technology upgradation and its management strategy has been recommended to significantly reduce all hazardous emissions to about 55% of the current measured values within 5-7 years both in summer and winter, enabling turning around of this city to safe vehicular emission levels. A global long term (15-20 years) zero emission vehicle technology strategy is also reviewed. Innovative collaborative emission control programme management structures are also recommended to be realized in three stages, addressing both technical and non-technical factors that currently enhance air pollution in Delhi.

Keywords: *vehicular air pollution, systems approach to emission control, catalytic converters, Non-thermal plasma devices, retrofitment, zero emission vehicles*

Cite This Article: R.Gopalaswami, "An Integrated Vehicular Emission Control Programme for the City of Delhi Using Retrofitted Emission Control Technologies." *Journal of Atmospheric Pollution*, vol. 4, no. 1 (2016): 1-14. doi: 10.12691/jap-4-1-1.

1. Introduction

Matthew [1] of the Indian Institute of Technology, Bombay defined Air Pollution as the disruption caused to the natural atmospheric environment by the introduction of certain chemical substances, gases or particulate matter, which cause discomfort and harm to structures and living organisms including plants, animals and humans. It has become a major concern in most of the countries of the world. It is responsible for causing respiratory diseases, cancers and serious other ailments. Besides the health effects, air pollution also contributes to high economic losses. Poor ambient air quality is a major concern, mostly in urban areas. Air pollution is also responsible for serious phenomena such as acid rain and global warming; due to vehicles, the cause may be evaporative or exhaust emissions.

Vehicular Pollution Problems in India Vehicular pollution contributes to 68% of air pollution in the city of Delhi. Sengupta [2] of the Central Pollution Board, Government of India, identified many technical and non-technical factors that cause vehicular air pollution:

Technical Factors

1. High vehicle density in Indian urban centers
2. Predominance of two stroke two wheelers
3. Adulteration of fuel & fuel products
4. Inadequate inspection & maintenance facilities
5. Older vehicles predominant in vehicle vintage

Non-Technical Factors

1. Improper traffic management system & road conditions
2. High levels of pollution at traffic intersections

3. Absence of effective mass rapid transport system &intra-city railway networks
4. High population exodus to the urban centers.

This paper deals only Technical Factors and suggests Technical Policy measures. It is expected that the management systems approach suggested will thereafter address non-technical factors, With this technical policy instrument alone, the recommended technical strategy for emission control targets air pollution in Delhi caused by vehicular emissions to be reduced by a substantial amount in the next 5-7 years, in a time bound manner with a systems approach using advanced emission control technologies that comprehensively addresses exhaust emissions that are emitted through the exhaust pipe namely:

- **a) Startup emissions:** Emissions when the vehicle is started initially. Based on how long the vehicle had been turned off after use, they may be cold start and hot start. Cold start refers to when the vehicle is started suddenly after a long gap of use, whereas, hot start refers to when the vehicle is started without the vehicle getting enough time to cool off after its previous use.
- **b) Running emissions:** Emissions during normal running of the vehicle, i.e., when the vehicle is in a hot stabilized mode.

The issue of evaporative emissions, though of marginal importance, include running losses and hot soak emissions produced from fuel evaporation when an engine is still hot at the end of a trip, and diurnal emissions (daily temperature variations) is mentioned for awareness and action.

2. Materials and Methods

The approach to formulating a comprehensive solution to air pollution in a major metropolitan city involves gathering information for detailed understanding of the sources, seasonal variation and the scale of pollutants in the city's atmosphere.

Air Pollution Levels In Delhi The Delhi government is of the view that high traffic volume is the principal reason for alarming increase of air pollution in the winter of December 2015. From 01 January to 15 January 2016 traffic levels were deliberately reduced by policy measures. The results in terms of reduced air pollution are yet to be published. Thereafter the Government has decided to repeat this experiment in summer, in April 2016.

Sources of Air Pollution in Delhi: Contribution by Weather. The US Embassy in New Delhi however publishes air pollution for a single particulate component PM 2.5, over Delhi day and night throughout the year including Sundays and holidays when traffic volume reduces as most people remain at home. A recent (unpublished) Study carried out by the author with this data revealed that for 3 months in the year, in Delhi's winter season, namely November to January (Figure 1), the local weather conditions, in terms of lower temperatures and lower dew points i.e. cold wet air hence with high "moisture-density" points out another significant factor, weather, as responsible for unhealthy/hazardous air pollution, amplifying urban air pollution due to vehicular, industrial and domestic air pollution. In 2009, Delhi was the fourth most polluted city in the world in terms of Suspended Particulate Matter, according to the to the World Health Organization Delhi. *By 2015 Delhi was characterized as among the world's most polluted city.*

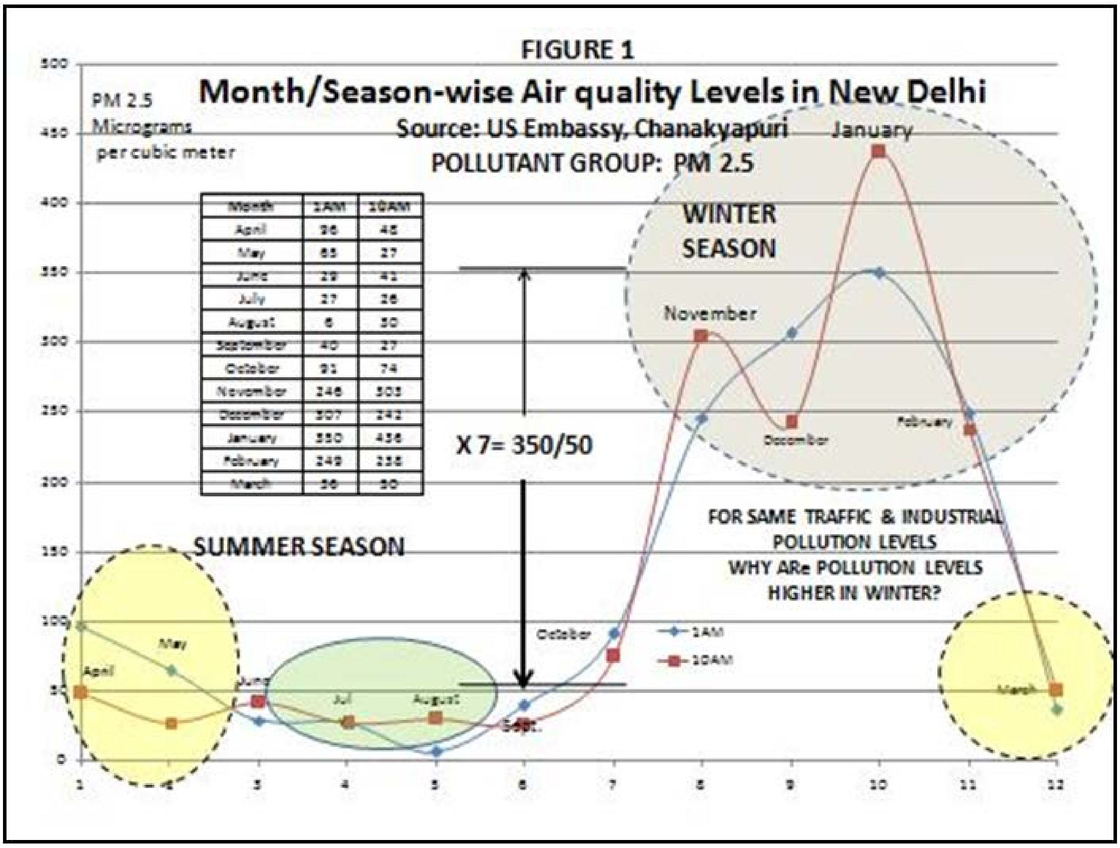

Figure 1.

From this limited Study based on published reliable longitudinal data it was observed reducing the traffic flow in winter may (counter intuitively) actually lead to an increase of pollution by as high as 50% as recorded in the Chanakyapuri locality of Delhi. (Figure 2). To establish this conclusively, very clearly a more comprehensive and complete analysis and modeling of air pollution in the city of Delhi (beyond the scope of this paper) is urgently needed using modern, sophisticated tools like the Gaussian plume model to analytically solve steady and unsteady transport equations including the effects of particle deposition and settling.

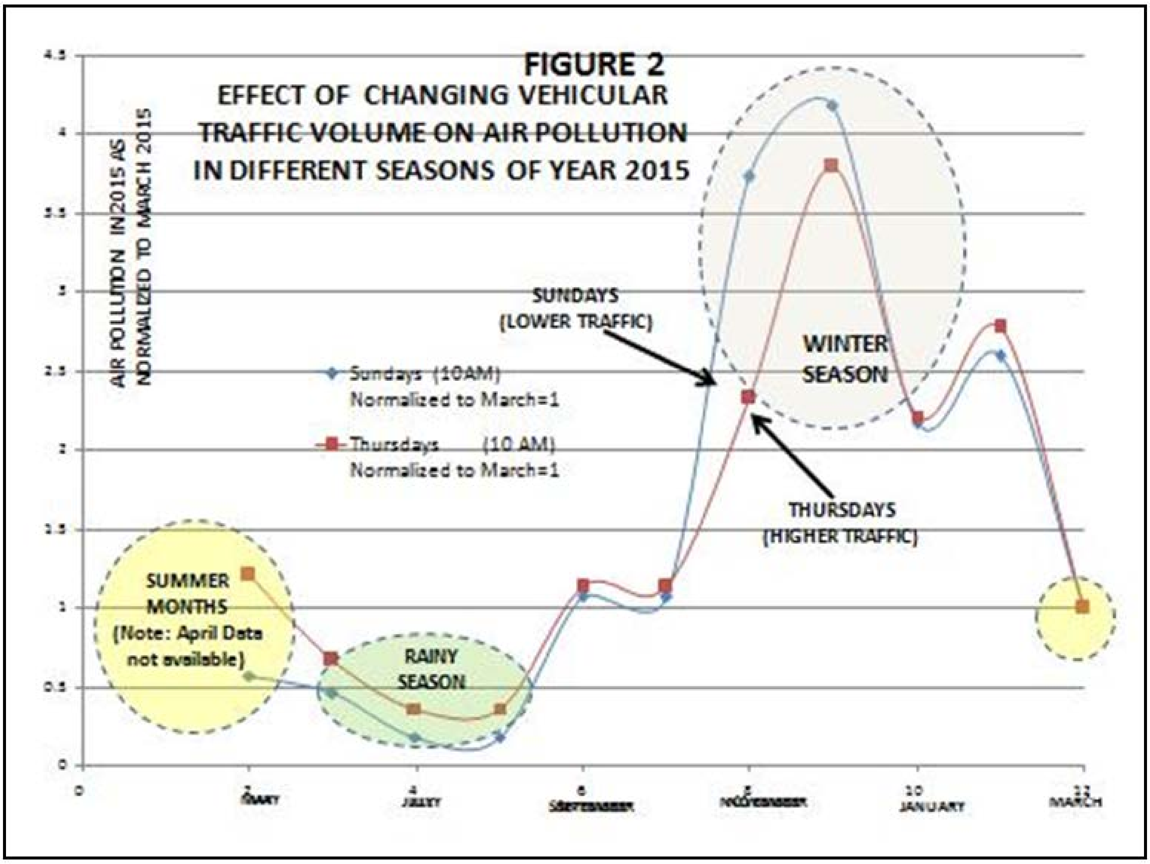

Figure 2.

There is no known way to change these climatic conditions that for 3 months of Delhi winters actually increase air pollution by 700% over summer and rainy season values. From this data and analysis (Figure 2), it seems unlikely that mere reduction in traffic volume will have a very significant impact on reducing air pollution in winter months; though in summer months and rainy seasons the levels were already in the allowable but tangible regions (Table 1).

Table 1. Classification of Seasonal Variation of Air Pollution in Delhi and Effects on Human Health

Data Extracted from Study Source			**Data Provided in US Embassy New Delhi Web Site**
Month	**1AM**	**10AM**	**Effect on Human Health [3]**
March	36	50	**Good (Allowable)** In this period April to September 2015, i.e. in Summer and in the Rainy Seasons air, pollution is NOT a serious problem, because at these levels PM2.5 air pollution poses little or no risk. Hence for 7 months or 58% of the year, Delhi is not seriously affected by pollution due to vehicular traffic emissions as well as due to industrial pollutions from its nearby thermal power stations. In these 7 months the city CANNOT e described as the world's most polluted city. This is a GOOD period for Delhi in regard to low levels of air pollution. The best month when the air in Delhi is washed clear of its pollution is JULY with the onset of rainfall and thundershowers of the rainy seasons
April	96	48	
May	65	27	
June	29	41	
July	27	26	
August	6	30	
September	40	27	
October	91	74	**Moderate** air pollution health risks here. After the rainy season, air pollution starts increasing in Delhi as temperatures fall and moisture content in air increases. Unusually sensitive individuals may experience respiratory symptoms.
November	246	303	**Very Unhealthy** (201-300). Significant aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; significant increase in respiratory effects in general population.
December	307	242	**Hazardous** (301-500). Serious aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; serious risk of respiratory effects in general population.
January	350	436	
February	249	238	**Very Unhealthy** (201-300). Significant aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; significant increase in respiratory effects in general population.

The objective of this paper is therefore to suggest a comprehensive solution to vehicular air pollution by addressing the problem at its root, namely on advances in technology of the internal combustion engine itself designed to increase combustion efficiency and reduce harmful emissions. So far this has not been attempted in an organized manner on a large scale. Hence an Integrated Vehicular Emission Control Programme specially designed for the City of Delhi by extensive use of advanced Emission Control Technologies is conceived herein and presented.

Sources of Air Pollution in Delhi: Contribution by Vehicular Traffic Rizwan et al. [4] In a report by the Government of India's Ministry of Environment and Forests, India, in 1997 reviewed the environmental situation in Delhi over concerns of deteriorating conditions Air pollution was one of the areas of concern identified in this study. It was estimated that about 3000 metric tons of air pollutants were emitted every day in Delhi, with a major contribution from vehicular pollution (67%), followed by coal-based thermal power plants (12%). There was a rising trend from 1989 to 1997 as monitored by the Central Pollution Control Board (CPCB). The concentrations of carbon monoxide from vehicular emissions in 1996 showed an increase of 92% over the values observed in 1989, consequent upon the increase in vehicular population. The particulate lead concentrations appeared to be in control; this was attributable to the de-leading of petrol and restrictions on lead-handling industrial units. Delhi has the highest cluster of small-scale industries in India that contribute to 12% of air pollutants along with other industrial units. Air pollution was one of the areas of concern identified in this study. It was then estimated that about 3000 metric tons of air pollutants were then every day in Delhi (estimated to be over 9000 tonnes/day in 2015) with a major contribution from vehicular pollution (67%), followed by coal-based thermal power plants (12%). There was a rising trend from 1989 to 1997 as monitored by the Central Pollution Control Board (CPCB).

Delhi has the highest cluster of small-scale industries in India that contribute to 12% of air pollutants along with other industrial units. It is presumed that the remaining 9% was due to domestic pollution cause by people living outdoors in winters and burning coal and wood fires in cold open air. This component would be absent in summer.

The various sources of air pollution in Delhi in winter and summer are shown in Table 2. It can be seen that ***vehicular traffic is the principal contributor to high level of air pollution in Delhi and hence calls for fundamental technological level solutions as the best method to resolve this problem.***

Table 2. Sources of Air Pollution in Delhi Rizwan et al. Report by the Ministry of Environment and Forests, India, 1997 [4]

Source of Air Pollution	Season	Contribution to Air Pollution	
		Winter Season	Summer & Rainy Season
Vehicular	All	67%	74%
Coal Based Thermal Power Stations	All	12%	*13%*
Industrial	All	12%	13%
Domestic Outdoor Living	Winter Months December/January	9%	NIL
Total		100%	100%

Scale of Vehicular Air Pollution in Delhi The total vehicle population of Delhi does of course play a very significant role in generating the scale of vehicular air pollution. According to the Registrations by Delhi Police as of 31 March 2015 is shown in the Table 3. It is seen that private vehicles like cars, scooters and motorcycles dominate the roads in approximately equal proportions, around 30% each. Other 4-wheeler commercial vehicles and LMVs constitute another small fraction, just 3.5%.

Public transport buses and auto-rickshaws constitute barely 1% of the vehicular population, less than mopeds in Delhi! These public transports are mostly driven by CNG which is least polluting. When the vehicles are analysed as Two- and Three –Wheelers the distribution in Delhi is indicated in Table 4. It can be seen that 65% of traffic is made up of 2-wheelers; and 34% of 4-wheelers, with three wheeler auto-rickshaws contributing to barely 1% of vehicular population. The case for substantially increasing public mass transportation in Delhi is paramount and well known to the Delhi authorities.

Table 3. Total Vehicles in Delhi as on 31 March 2015 From Delhi Police Register [5]

Vehicle	Numbers (N)	Percentage of Total
Car	2640809	30.3%
Scooter	2716045	31.1%
Moped	105114	1.2%
Motor Cycle	2862581	32.8%
Auto-rickshaw	81306	0.9%
Bus	19694	0.2%
LMV	83527	1.0%
Other Commercial 4-wheelers	220521	2.5%
Total	8729597	100.0%

Table 4. Two-and Three-Wheeler Population in Delhi on 31 March 2015 (Derived from Table 3)

All Vehicles (Including CNG)	Numbers	%age number
4-wheelers	2964551	0.34
3-wheelers (Mostly CNG)	81306	0.01
2-wheelers	5683740	0.65
Total	8729597	1.00

Fuel Consumption Analysis A study of the fuel consumption pattern of the vehicle portfolio of Delhi requires knowledge/data on the **Average Distance Travelled per Day** by different types of vehicle. This has been reported by Narain and Krupnik in a February 2007 Study [6] and is shown in Table 5.

Table 5. Average Kilometers Traveled Per Day by Vehicles in Delhi

Vehicle	Distance Travelled per day (Kilometers)
Bus	157.2
Three-wheeler	66.5
Taxis	45.1
Cars	36.6
Trucks	39.7
Two-Wheelers	36.4

The **Average Fuel Consumption** of different types of vehicles in India as obtained from reliable internet sources are shown in Table 6. Based on the Data (Table 5 & Table 6) the scale of fuel consumption in Delhi per year for all vehicles has been analysed and estimated and shown in Table 7. Nearly 9 million vehicles cover over 100 billion kilometers every year spewing nearly 4 million tonnes of fuel emissions into the atmosphere every year (9900 tonnes per day). About 1.6 Kg of rubber gets worn out every 32,000 Kms, as calculated from [7]. This wear out of tyres on Delhi roads adds 5945 tonnes of rubber per year (about 16 tonnes of rubber per day!). The impact of 4-wheeler and 2-wheelers on emissions is analyzed in Table 8.

Table 6. Average Fuel Consumption of Vehicles in India (Sourced from Internet)

Vehicles in India	Average Fuel Consumption (Kms/Litre)
Car	15
Scooter	45
Moped	60
Motor Cycle	70
Auto-rickshaw (Mostly CNG)	20
Bus (Mostly CNG)	4
LMV	12
Other Commercial 4-wheelers	12

Characteristics of Vehicular Traffic & Type-Wise Vehicle Emissions in Delhi The total Vehicle Population of Delhi does of course play a very significant role in generating the total volume of vehicular air pollution. According to the Registrations by Delhi Police as of 31 March 2015 is shown in the Table 3. It is seen that private vehicles like cars, scooters and motorcycles dominate the roads in approximately equal proportions, around 30% each. Other 4-wheeler commercial vehicles and LMVs constitute another small fraction, just 3.5%.

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Table 7. Analysis of Fuel Consumption of Vehicles in Delhi (From Tables 3 to 6)

Vehicle	Numbers (N)	Average Use of Vehicles Kms/Day (From Table 5) (D)	Average Total Billions of Kilometers per Year K= N*D*365	Average Fuel Consumption (From Table 6) (f) (Kms/Litre)	Total Fuel Consumed per year [(K/f)*0.8]/1000 (Tonnes)	Total Fuel Consumed per Day (Tonnes)	% of total fuel consumed	Percentage of Total Vehicles
Car	2640809	36.6	35	15	1881524	5155	52%	30.3%
Scooter	2716045	36.4	36	45	641518	1758	18%	31.1%
Moped	105114	36.4	1	60	18621	51	1%	1.2%
Motor Cycle	2862581	36.4	38	70	434654	1191	12%	32.8%
Auto-rickshaw	81306	66.5	2	20	78940	216	2%	0.9%
Bus	19694	157.2	1	4	226000	619	6%	0.2%
LMV	83527	45.1	1	12	91665	251	3%	1.0%
Other Commercial 4-wheelers	220521	45.1	4	12	242007	663	7%	2.5%
Total	8729597		119		3614929	9904	100.0%	100.0%

Table 8. Analysis of Fuel Consumption of Vehicles with Four-stroke and Two-stroke Engines in Delhi

Vehicle	% of total fuel consumed	Percentage of Total Vehicles	Classification according to Engines	% of total fuel consumed	Percentage of Total Vehicles
Car	52%	30.3%	Four Wheelers (Four Stroke Engines)	68%	34%
Bus	6%	0.2%			
LMV	3%	1.0%			
Other Commercial 4-wheelers	7%	2.5%			
Scooter	18%	31.1%	Two Wheelers (Mainly Two Stroke Engines)	30%	65.1%
Moped	1%	1.2%			
Motor Cycle	12%	32.8%			
Auto-rickshaw	2%	0.9%	Three Wheelers (Mainly Two Stroke Engines)	2%	0.9%

3. Systems Approach to Large Scale Deployment of Advanced Vehicular Emission Control Technologies

Technology Options for Vehicular Emission Control Vehicular Emission Control is a large technical challenge will require a *systems-based approach* combining, fuel formulation with elements of engine modifications, fuel pre-combustion treatment (before fuel injection into the combustion chamber) and exhaust control technology (or after- combustion treatment) Common to all Emission Control Technologies are Fuel Formulations requiring Low-sulfur petrol & diesel. These are discussed in detail.

Emission Control Enabling Technology Strategies Advanced Emission Control Technologies are identified in this paper. Their technical characteristics are described fully in Appendix "A". However strategy implementation feasibility would be based on their utility as seen in Table 9.

Table 9. Emission Control Technologies

<table>
<tr><th colspan="6">Emission Control Technology Implementation Feasibility</th></tr>
<tr><td colspan="2">(A) Changes feasible only by Car/Engine manufacturer.
Retro-fitment not feasible in older engines.</td><td colspan="4">(B) Retro-fitment feasible even for older vehicles</td></tr>
<tr><td colspan="4">Purpose: To Improve Combustion Efficiency
For Reducing Harmful Emissions & Reducing Fuel Consumption</td><td colspan="2">Purpose: To Clean Up Exhaust Emissions</td></tr>
<tr><td colspan="2" rowspan="2">(A1) Improved Engine Design
to meet tight Bharat/Euro Emission Control Standards</td><td colspan="2">(B1) Pre-Combustion Treatment
Fuel Droplet Atomization , Shattering & Mixing Technologies</td><td>(B2) After –combustion
Treatment [8]</td><td rowspan="2">(B3)To Eliminate Cold Start</td></tr>
<tr><td>B1.2 Water Injection, Emulsified Fuels, Oxygen Injection</td><td>B1.3 Energized Fuels</td><td>(B2.1) Exhaust Control Technology</td></tr>
<tr><td>Electronic ignition, more precise fuel metering, and computerized engine management</td><td>Catalytic Converter With/without Secondary Air Injection
• Substrate & coating technologies
• Three-way catalysts for NO_x reduction
• Oxidation catalysts
• Exhaust gas recirculation</td><td>B1.2.1
Water Injection, Emulsified Fuels, Oxygen Injection For diesel Engines only [9]</td><td>B1.3.1 Fuel-Borne Catalyst (FBC)
B1.3.2
Non-thermal plasma devices</td><td>B2.1.1Catalytic Converter With/without Secondary Air Injection
• Substrate & coating technologies
• Three-way catalysts for NO_x reduction
• Oxidation catalysts
• B2.1.2. Diesel Particulate filters
• B2.1.3. Wall-flow filters
• B2.1.4 Open flow filters
• B2.1.5 Urea injection
• B2.1..6 Lean NOx Traps (LNT)
• B2.1.7. Plasma assisted catalysis</td><td>B3.1 Electrical heating of cat con

B3.2 Non-thermal plasma devices</td></tr>
<tr><td colspan="6">(C) Zero Emission Vehicles: Enabling Technologies
US State of California Report (Reviewed in Appendix 'A') [10]</td></tr>
<tr><td colspan="2">(C1) Energy Storage Batteries</td><td colspan="2">(C2) Hydrogen Fuel Storage</td><td colspan="2">(C3) Fuel Cells</td></tr>
<tr><td colspan="2">• C1.1 Nickel Metal Hydride Batteries (NiMH)
• C1.2 Lithium Ion Batteries (Li Ion)
• C1.3 ZEBRA (sodium-nickel chloride) Batteries</td><td colspan="2">• C2.1 Gaseous hydrogen 350 bar
• C2.2 Gaseous hydrogen 700 bar
• C2.3 Liquid hydrogen (has limitations)
• C2.4 Adsorbed Hydrogen (far term)</td><td colspan="2">Review in Appendix "A"</td></tr>
</table>

Improved Engine Design & Emission Standards Bharat Stage I, II, and III were introduced in 2000, 2001, and 2005 respectively for four-wheeled vehicles in Chennai. Bharat Stages I and II were introduced during 2000 and 2005 respectively for two- and three-wheelers and are the most stringent norms worldwide. Bharat Stage IV was implemented in 2010. It has now been proposed to skip Bharat Stage V and proceed straight to Bharat Stage VI. Such standards are implementable only by engine designers and manufacturers and this issue is not discussed further. This paper therefore is confined to

a) Retro-fitment of advanced Emission Control Technologies that is feasible *immediately* even for older vehicles (Immediate & Short –term strategy, 2016 to 2021/23)
b) Zero Emission Vehicles (A Global Long Term Strategy (2030-2035): a Review is set out in Appendix "A"

Automobile Fuel Quality & Impact on Emissions The controversies regarding fuel formulations i.e. quality of fuel were quite intense when Emission Standards were first introduced in 1990's. A first-ever environmental audit of the Indian automobile industry carried out by the Centre for Science and Environment (CSE) [11], Delhi, which began its Green Ratings project in 1996, with the support of the UNDP and the Indian Union Ministry of Environment and Forests (MOEF). The CSE recommended that developing advanced technology to meet stringent standards may be the best way to reduce vehicular emissions.

4. Retro-Fitment of Advanced Emission Control Technologies & Programme for Delhi

Primary Target for Delhi's Emission Control Regime Hence it is clear that from this analysis supported by the CSE study that from emission control considerations, the *primary target* for an Emission Control Regime when formulated and implemented using a systems approach to retro-fitment of advanced emission control technology needs to FOCUS on the 4-wheeler population in Delhi (with first priority on diesel engines), followed by two-wheelers fitted with 2-stroke engines. Nesamani [12] in his comprehensive study and analysis of vehicular traffic and air pollution in another large metropolitan city in India (Chennai) reported that about 14% of the vehicles more than 5 years old (about one million) may be the worst polluters responsible for 60% of vehicular pollution. Twenty percent of poorly maintained vehicles produce about 60 percent of vehicular pollution in India (Pundir, 2001 as quoted by Nesamani [12]). Because of lax enforcement, only 10 percent of vehicles undergo the mandatory PUC which is ineffective in identifying the major polluters (Zubeda, 2007). Based on this Study, estimation here was carried out as indicated in Table 10.

Table 10

Total Vehicles in Delhi 2015	8,72,9597
Growth factor in Delhi for 5 years at 7% annual growth rate =(1.07)^%	1.4
Number of vehicles in Delhi in 2010 (i.e. a;; vehicles more than 5 years old)	6235426
No. of poorly maintained vehicles @ 14% (based on [12])	122,2143
Number of poorly maintained vehicles in 2015 at Growth Factor 1.4	1,71,1001
%age poorly maintained vehicles in Delhi in 2015	20%

Based on this tentative assumption (till validated by physical check) the actual number of 4- and 2-wheeler vehicles that are poorly maintained and hence need retro-fitment with advanced emission control technologies is estimated in Table 10. Estimated Scope (Tentative) of Retro-fitment Programme for each of 14 Advanced Emission Control Technologies is shown in Table 11.

It can be seen from Table 8 that the bulk of 68% of air pollution is caused by four-wheelers (constituting only 34% of vehicle population) while 30% by two-wheelers (65% of all vehicles). *Three wheelers are responsible only for a negligible part of air pollution, and burn "clean" CNG fuel (i.e. no particulate matter).* All these numbers present a strong case for the Delhi Administration to proceed at full speed ahead to introduce public mass transportation systems keeping the future zero-emission vehicle (ZEV) regime in mind (discussed later) with solar energy charged battery-powered busses and three wheeler

Retrofit Workshops in Delhi Over one million vehicles to be inspected and retrofitted may on the surface appear a daunting task. It will not be so if:

1. The actual engineering retro-fitment work assigned to about **100 special Emission Control Technology Retro-fitment Centre**s (set up by both private and public sector companies) in Delhi.
2. Their total engineering infrastructure (skilled labour and special tools) is built up to **complete the programme in 5 years** i.e. 1,000,000 retrofits at 200,000 polluting vehicles per year.
3. Each of the Centres is assigned a **retro-fitment task of 2000 vehicles per year** i.e. work round-the-clock producing and delivering about 5-6 retrofitted Vehicles per day i.e. **200,000 retrofits per year.**
4. Assuming an average cost of retro-fitment (*labour+ materials + overheads*) at about Rs.20,000 per vehicle the annual sales output of these 100 workshops would be Rs 20,000 x 200,000 vehicles per year = **Rs 400 crores per annum**, *or Rs 2000 crores to retrofit all polluting vehicles in Delhi.*
5. For an automobile engineering industry of this nature, Pavan Kumar [13] estimated the net sales-to-fixed assets ratio = 3.5 the total investment in 100 retrofit workshops would not exceed Rs 114 crores i.e. Rs. 1.14 crores per Retro-fitment Centre.

Table 11. Tentative Numbers of Poorly Maintained Vehicle Systems in Delhi to be Retro-fitted with Advanced Emission Control Technologies

All Vehicles (Including CNG)	Numbers (From Table 4)	Number of vehicles in 2010 (More than 5 Years old)	No. of poorly maintained vehicles @ 20% Of Vehicles More than 5-years Old	
4-wheelers	2964551	2117536	423507	Diesel @ 25% 105877 Petrol @ 75% 317630
2-wheelers	5683740	4059814	811963	4-stroke @ 25% 202991 2-stroke @ 75% 608972
Total	8729597	6235426	1247085 (14% of Total Registered Vehicles in Delhi)	

Table 12. Estimated Scope (Tentative) of Retro-fitment Programme for each of 14 Advanced Emission Control Technologies

Sl. No.	Purpose	Advanced Emission Control Technologies	Tentative Numbers of Poorly Maintained Vehicle Systems in Delhi To be Retro-fitted with Advanced Emission Control Technologies (From Table 10)			
			4-wheelers		2-Wheelers	
			Diesel @25% of Total	Petrol @75% of Total	2-stroke Petrol @75% of Total	4-stroke @25% of Total
			105,877	317,630	608,972	202,991
1	Fuel Droplet Atomization , Shattering & Mixing Technologies	Oxygen Injection				
2		Water Injection				
3		Emulsified Fuels				
4	Energized Fuels	Fuel-Borne Catalyst				
5		Non-thermal plasma devices				
6	Exhaust Control Technology	Catalytic Converter With/without Secondary Air Injection				
7		Diesel Particulate filters				
8		Wall-flow filters				
9		Open flow filters				
10		Urea injection				
11		Lean NOx Traps (LNT)				
12		Plasma assisted catalysis				
13	Cold Start Elimination Technology [12]	Electrical heating of cat con				
14		Non-thermal plasma devices				

Affordability As a comparison of this cost of 100 workshops at Rs 114 crores it may be noted that the *GDP of Delhi in 2014-15 was Rs 451,154 crores at current prices* so clearly this is an affordable proposal, needing only effective management systems to implement a sustainable Emission Control Regime. Indeed, if the collective will to implement were to be mustered, the entire programme could be completed within two years from supply aspects; but could take up to 5 years because of public participation in a democratic system of governance would be slow in picking up momentum.

Prioritization for Evaluation of Emission Control Technologies at Vehicular Level To prioritize emission control measures it may be observed that

1. A Centre for Science and Environment (CSE) study reported [14] that CNG was far better in terms of tailpipe emissions; having five times lower particulate matter and overall 73 per cent lower emissions than the diesel vehicles. This first-ever environmental audit of the Indian automobile industry reveals that much needs to be done before it can attain globally acceptable standards.
2. It may be seen from Table 8 that 68% of vehicular pollution is from 4-wheeelers, and 30% from 2-wheelers.
3. Overall petrol vehicles ranked better than diesel fuelled ones — all top 14 cars were petrol ones.
4. The carbon monoxide and hydrocarbons plus nitrogen oxides emitted by two stroke two-wheeler engines (even *with catalytic converter*) were 23 per cent (CO + hydrocarbon) and 38 per cent (NO_X) higher respectively than their 4-stroke equivalents *without catalytic converter*, according to the same Centre for Science and Environment (CSE) study report [14].

FIRST VEHICULAR PRIORITY Clearly, emission control at vehicular levels has to be evaluated with **first priority accorded to DIESEL CARS / HEAVY VEHICLES**. In turn, prioritization at emission control technology level would be

a) Diesel Engine Retrofitments Technology Priority 1

Catalytic Converter for retro-fitment in the exhaust manifold. These are already in quantity manufacture in India and made in millions world over for use directly by engine manufacturers (with/without Secondary Air Injection). India's has a competitive advantage in that over several years its R&D establishments (in civil and defence ministries) have developed new processes & technologies for catalytic converters as described in the Appendix. Even though emission standards in India demand the fitment of catalytic converters, inadequate maintenance & inspection makes it impossible to know how many cars are still without catalytic converters.

b) Diesel Engine Retrofitments Technology Priority 2

Non-thermal plasma device as an Advanced Fuel Injection Technology. A cost-effective advanced technology **called "Hydrodrive" has been** developed and comprehensively certified by several authorities in India (including the local State Pollution Control Board) and abroad. This advanced technology was developed and manufactured by an innovative, R&D intensive establishment in the private sector. More details are described in the Appendix.

c) Diesel Engine Retrofitments Technology Priority 3

Cold-start elimination technologies would need to be evaluated for retro-fitment in diesel engines. These include **electrical heaters for catalytic converters and Non-thermal plasma devices.** The status of availability/manufacture/R&D in India is not known in detail. More details are described in the Appendix

d) Diesel Engine Retrofitments Technology Priority 4: The following emission control technologies need to be evaluated for ease of retro-fitment in diesel engines. These include Oxygen Injection, Water Injection, Emulsified Fuels, Fuel-Borne Catalyst, Diesel Particulate filters, Wall-flow filters, Open flow filters, Urea injection and Lean NOx Traps (LNT).

The status of availability/manufacture /R&D in India is not known in detail. It is likely these technology retrofits are required to be done only by the engine manufacturer in their facilities. More details are described in

1. **FUEL BORNE CATALYSTS** http://www.cerionenergy.com/wp-ontent/uploads/ 2013 /03/Emissions-Reduction-via-Fuel-Borne-Catalysts.pdf Diesel Fuel Optimizer is a nanoparticle combustion catalyst suspended in a petroleum distillate
2. **OXYGEN ENRICHED INJECTORS** Bhavin Mehta, Hardik Patel Pushpak Patel *"Opportunity to improve the Engine Performance and Emission Characteristics by using Oxygen Enriched Combustion"* Mechanical Department, Mechanical Department, Mechanical Department, C.S.P.I.T, Charusat.
3. **WATER INJECTOR FOR DIESEL ENGINES** https://www.google.co.in/imgres?imgurl=https% 3A%2F%2Fwww.dieselnet.com%2Ftech%2Fima ges%2Fengine%

SECOND VEHICULAR PRIORITY Emission control at vehicular levels has to be evaluated with **second priority accorded to Petrol CARS / HEAVY VEHICLES**. In turn, prioritization at emission control technology level would be

1. **Catalytic converter**s as for diesel engines
2. **Non-thermal plasma device** as an Advanced Fuel Injection Technology (as for diesel engines).
3. **Cold-start elimination technologies** would need to be evaluated for retro-fitment in petrol engines as for diesel engines.

THIRD VEHICULAR PRIORITY Emission control at vehicular levels has to be evaluated with **second priority accorded to 2-Wheelers**. In turn, prioritization at emission control technology level would be:

1. Two Stroke engines :
   a. **Non-thermal plasma device** as an Advanced Fuel Injection Technology (details in Appendix "A").
   b. Catalytic converter (needs to be specifically developed)
2. Four Stroke engines:
   a. **Non-thermal plasma device** as an Advanced Fuel Injection Technology
   b. Catalytic converter (needs to be specifically developed)
   c. Combination of (a) and (b)

FOURTH VEHICULAR PRIORITY The ultimate solution, Zero Emission Vehicles. More details are described in the Appendix. Policy planning for ZEVs needs to be taken up on highest priority.

5. Integrated Programme Management Organization

Targets for Delhi's Emission Control Programme Emission control targets considered achievable by retro-fitment of advanced emission control technologies have been identified for different sources and seasons and suggested in Table 13. Exceedingly low targets for air pollution from thermal power stations and Delhi's industries have been indicated for the first five years, by which time the momentum and direction of overall environmental protection efforts in Delhi might have gained momentum.

6. Results of the Programme for Vehicular Emission Control in Delhi

The overall reduction of emission causing air pollution in Delhi due to a sustainable emission control regime has been estimated. The results are also shown in Table 13 below.

Table 13. Emission Control Targets for Delhi by 2020

Source of Air Pollution	Season	Contribution to Air Pollution (Current in 2015) (A)		Pollution Reduction by Technology Upgradation (Target by 2020) (B)	Contribution to Air Pollution After Pollution Reduction Programme (Target by 2020) (A x B)	
		Summer & Rainy Season	Winter Season		Summer & Rainy Season	Winter Season
Vehicular	All	74%	67%	70%	52%	47%
Coal Based Thermal Power Stations	All	13%	12%	10%	1.3%	1.2%
Industrial	All	13%	12%	10%	1.3%	1.2%
Domestic (Outdoor Living)	Winter Months December/January	NIL	9%	70%	NIL	3%
Total		100%	100%		54.6 %	52.4%
Measured Value of Air Pollution (Respirable Suspended Particulate Matter (RSPM) PM 2.5 Micrograms/Cu. m		< 50 (Tending to be safe)	>350 (Hazardous to health)		< 30 (Best among the world's cities for 7-8 months)	< 185 (Moderate risks to unhealthy for sensitive groups health)

Thus it is seen that a comprehensive, integrated approach to emission control in Delhi can reduce the air pollution in Delhi to about 55% of its current levels, not taking into account the substantial savings in fuel consumption that would motivate citizens to support the Emission Control Regime. This is feasible by the fourteen enabling new and advanced technologies which have been identified for immediate test, evaluation, and deployment where found suitable based on a prioritized assessment of each vehicle's need.

Several of these advanced technologies have already been fully developed and extensively certified in India in defence and civil R&D establishments in the Central Government as described in Appendix "A". Yet these technologies are perhaps are not known to leave alone their technology transferred to State Governments/private automobile industries for adaptation and vehicle-specific commercialization The recommended technology upgradation and its management strategy has the potential to significantly reduce hazardous emissions to less than 55% of the measured values within 5-7 years, both in summer and winter enabling turning around of this city to safe vehicular emission levels.

A long term (15-20 years) zero emission vehicle technology strategy is also identified in Appendix "A". Innovative collaborative emission control programme management structures are also recommended to be realized in three stages, addressing both technical and non-technical factors that enhance air pollution in Delhi.

In the **First Stage (Evaluation),** the actual numbers (type-wise and registration number-wise) of vehicles responsible for vehicular air pollution is ascertained and compiled by the Delhi Administration. Thereafter, in collaboration with DPCB/CPCB, Delhi Administration sets up a small Project Team of automobile engineering and emission experts. The Team advertises globally and identifies firms/organizations in private and public sectors engaged in R&D/manufacture of new/advanced emission control technologies in India and abroad. After taking presentations and discussions the Project Team could make a preliminary choice among competing options.

In **Stage 2 (Experimentation),** the Project Team plans and conducts a Pilot Emission Control Study on a total of about 500 highly polluting vehicles, retrofitting about 5 vehicles per day for 100 days, drawn from of the worst polluting vehicles on Delhi roads today, drawn appropriately from 4-wheeler and 2-wheeler population, and enable retro-fitments carried out in small/medium scale industries by public-private partnerships at a cost of about Rs 1 to 2 crores. The results may be analysed by an independent team of experts in terms of emission control effectiveness, and technical/commercial/ economic viability. The economics and affordability of emission control technology retro-fitment programme management as indicated in this paper may be confirmed /validated at this Stage.

Stage 3 (Consolidation & Expansion) starts after a Cabinet-level decision of the Delhi Government is taken for a full scale emission control technology absorption programme, coordinated by a core Integrated Vehicular Emission Control Programme Management Organization (EPMO) responsible to the Delhi Administration. The EPMO is designed to make the mission truly collaborative and inclusive, with experts and policy makers from the Delhi and Central Governments (especially the Ministries of Transport, Petroleum and Environment). A small (permanent) Vehicular Emission Control Technology Exhibition in Delhi, hosting Indian and foreign developers/producers/suppliers to display the entire spectrum of emission control technologies; and effective endorsement of the programme by the national media would enable gaining wider public acceptance of the programme in Delhi and appreciation by the whole country.

The comprehensive programme would call for **100 special Retrofit Centres** are suggested costing Rs 114 crores with a sales turnover of Rs 400 crores per annum to complete retrofit of over one million vehicles within 5 years for a capital city whose GDP is worth over Rs 450,000 crores. This is clearly an affordable proposal as well ($1.0 million = Rs 6.60 crores currently).

A specially trained **Vehicular Emission Standards Enforcement Organization** Called VECTOR (Vehicular Emission Control Compliance Task Force) needs to be set up by the EPMO. This may be partially drawn from but are not dependent on the Delhi Traffic Police. It would be essential to create a mission-specific Consortium of Emission Control Technology Upgradation Centres in Delhi and India to back up the technical aspects of the programme. Finally, a **Delhi Environmental Protection Agency** would emerge for evaluation, control and monitoring of all air, water and ground pollution organizations in Delhi in close coordination with the Delhi and the Central Pollution Monitoring Board.

7. Conclusion

These technological, management and policy measures would making this the most comprehensive Emission Control Programmes ever undertaken anywhere in the world; and shape the future of the Capital City of India as one among the cleanest in the world, rapidly emulated in other cities and towns nationwide.

Acknowledgement

The author is grateful to **Dr. E.A.S Sarma IAS (Retd.)**, formerly Secretary (Power) and Secretary (Finance) in the Government of India, to have kindly reviewed the paper at different stages while offering invaluable insightful comments. He is also thankful to **Sri. S.Gopalakrishnan**, in Chennai, a retired automobile industrialist who has been deeply committed to research and development of advanced, innovative, indigenous control technologies for nearly two decades. His contribution to safety aspects of introducing new emission control technologies is particularly appreciated. To **Dr K.S. Nesamani**, Air Resources Engineer at California Air Resources Board, Sacramento, California, for sharing his thoughts based on his extensive studies on vehicular pollution in the city of Chennai.

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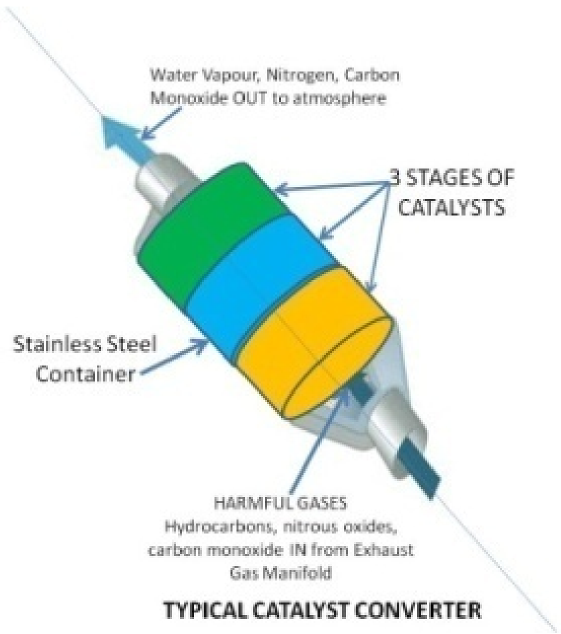
Appendix "A"

The Foundations of Advanced Exhaust Control Technologies

(Source: *Indigenous ceramic catalytic converters*, Hindu Business Line Financial Daily from THE HINDU group of publications Wednesday, June 13, 2001)



How the Catcon Works A catalytic converter is a device fitted into the exhaust system of the vehicle. It helps in chemically changing polluting material such as carbon monoxide, hydrocarbons and oxides of nitrogen as well as particulate matter into harmless substances before releasing them into the environment.

As shown in the typical catalytic converter, noxious and harmful hydrocarbons, carbon monoxide and nitrous oxides are oxidized by the catalyst in the high exhaust gas temperatures which converts these harmful emissions into harmless constituents normally found in the atmosphere.

In India, catalytic converters have been developed by various Government owned or Public Sector laboratories, including the

1. National Environment Engineering Research Institute (NEERI), Nagpur.
2. The Research and Development Centre of Indian Oil Corporation (IOC), at Faridabad.
3. The Indian Institute of Petroleum (IIP), Dehradun.

In addition, several players in the private sector have tied up with international manufacturers to import/produce a range of catalytic converters. They have developed catalytic converters for both petrol- and diesel-driven two-stroke and four-stroke vehicles. *The device works out 40-45 per cent cheaper in the case of petrol, and 50-55 per cent less in diesel, when compared to an imported version.* The main components of the device are a particulate filter, which is wash-coated, a ceramic honeycomb with a catalyst and a metallic can which houses the complete assembly. This includes the high alumina wash-coat, which helps increase the surface area, and a platinum-palladium-rhodium catalyst. ARCI has specialized and provides ceramic honeycomb structure to private players.

The catalytic converter developed by private companies are put through tests by various OEMs, especially for diesel engines, at the Automotive Research Association of India (ARAI), Pune, and the Vehicle Research and Development Establishment (VRDE), under the Defence Ministry so as to meet the existing emission standards being implemented in the country by the Ministry of Environment and Surface Transport.

US EPA Publication [15] on Safety precautions during use of retrofitted catalytic converters Millions of catalytic converters are in continuous operation world over. However the introduction of an additional hot chamber adjacent to the existing exhaust system introduces an additional hot surface beneath the car. Users need to be cautioned not to park/drive the vehicle over dry grass/leaves. The vehicle manufacturers are aware of the need to provide protection from possible hazards or discomfort associated with high catalyst temperatures for both the vehicle occupants and vehicle components. In addition, protection is also necessary to avert possible fire hazards associated with driving vehicles through tall grass or other vegetation.

The exact means taken by the different manufacturers to provide high temperature protection vary, and include such approaches as insulating the entire catalytic reactor so that the outside surfaces are not hotter than mufflers, installing protective metal shields between the converter shell and vegetation, and using thicker carpeting materials inside the car to protect the occupants from experiencing high floorboard temperatures. In addition, some cars have temperature-sensing devices to deactivate the catalytic reactor or alert the driver to abnormally high temperatures, which might be caused by misfiring spark plugs, etc.

In the USA, the Environmental Protection Agency and National Highway Traffic Safety Association have been monitoring closely the frequency and type of such incidents. The NHTSA, on the basis of a review completed in December 1976, concluded that "the rate and nature of catalytic converter incidents do not present an unreasonable risk of health or injury to the public." The EPA will continue to require manufacturers to design their vehicles so that when properly operated and maintained they will pose no hazard to either life or property.

In the case of India's Retro-fitment programme, a specially trained vehicular emission standards enforcement organization called VECTOR (Vehicular Emission Control Compliance Task Force) needs to be set up by the EPMO. This may be partially drawn from but are not dependent on the Delhi Traffic Police. VECTOR would also set up a chain of *Emission Control Technology Inspection & Maintenance Centres located along with the Retrofit Centres* and new users would be informed about need for regular check-up of emission control devices especially catalyst converters.

Non-thermal Plasma Device: Nanotechnology at the Heart of Fuel Energizers

(Source: The Hindu Thursday, Nov 20, 2003 http://www.thehindu.com/seta/2003/11/20/stories/2003112000090200.htm) [16]

The Non-thermal Plasma Device called "Electronic Catalyst Converter" or "Hydrodrive" is an economical retrofit for meeting Euro II norms by most of the pre 1996 vehicles. It is installed in the fuel system after the fuel filter outlet and before the fuel injection pump inlet or the carburetor. The unit is powered by the vehicle's existing 12V battery through the ignition switch. *The device consists of nano structure co-axial wave-guide within a microwave dielectric cavity resonator.*

Electronic Catalytic Converter
http://www.hydrodrive.co.in/ECC.htm?ckattempt=1
(Image with Permission)

Detailed information is available at the following websites:

1. http://www.linkedin.com/in/srinivasangopalakrishnan
2. http://www.hydrodrive.co.in/S.GOPALAKRISHNAN.htm
3. http://www.hydrodrive.co.in/NEWS.htm
4. www.hydrodrive.co.in
5. http://www.youtube.com/watch?v=JREBz-Jhi1M
6. https://www.youtube.com/watch?v=y4mUzdbZTmw&feature=youtube_gdata_player
7. How Hydrodrive electronic catalytic convertor works?
8. http://www.slideshare.net/hydrodrive/an-invention-in-multiple-applications
9. An invention having social and economic relevance in multiple applications patented in several countries: https://www.youtube.com/watch?v=cL6UVIDWqxk What do the users say ?

PERFORMANCE The highlight of the converter is its ability to reduce diesel smoke by over 70 per cent. Particulate emissions are reduced by over 60 per cent. In the gasoline engines, the carbon monoxide emissions are less than 0.1 per cent by volume and HC emissions are less than 200 ppm for most of the pre 1996 vehicles. With Euro II vehicles fitted with an exhaust converter, the retrofit brings down the emissions almost to zero level in most of the cars. Fuel savings of more than 7 - 10 per cent in real working conditions with normal commercial fuels are achieved. The novelty of the invention is that one common unit measuring one foot long, one inch in diameter and weighing one kilogram handles all the fuels and also effectively works from a small car to a giant diesel power generation set such as the 908 horsepower Caterpillar and 1000 DWT ship engines.

WORKING PRINCIPLE When the fuels pass through the electronic catalytic converter, the fuel molecules are excited by the microwaves and **cold plasma waves from the nano wire arrays**. With the waves adiabatically compressed, the fuel molecules undergo conformational changes, viscosity and density changes on account of dipole and ionic conduction phenomenon of the molecules interacting with the electric field component of the microwave. The density, viscosity, activation energy, enthalpy changes of the fuel molecules in real time during flow within the nano structure wave guide improves the fuel quality onboard in real time and changes the chemical rate constant and kinetics of combustion. This results in improved engine performance such as smoother engine as experienced with higher octane fuels or high cetane diesel facilitating reduced emissions and improved fuel economy. The science employed in the converter namely the nano structure based wave guide, plasma waves in the microwave and millimeter region in the nano wires are now confirmed by research papers published in international journals. These confirmations have helped widen the scope of applications in a host of areas such as pharmaceuticals, and chemical and refrigeration industry, conversion of gasoline into gaseous fuel. The catalytic converter can find application in nearly 20-25 more areas.

Certification The Tamil Nadu Pollution Control Board had certified its efficiency in controlling emission. Several users had also tested its performance on road. The world Intellectual Property Organization at Geneva has notified this invention for the grant of a patent in 95 countries. Having won the Asian Innovation Award Gold in 2001 presented by the Dow Jones Group-Far Eastern Economic Review, Hong Kong, it is currently being exported to the Philippines, China and Bangladesh. Renowned vehicle manufacturers - Isuzu Motors, Mitsubishi Motors Corporation, KIA Motors have tested and certified the performance of the unit with their vehicles and engines for both emission reductions and fuel savings in actual driving conditions with regular commercial outlet fuels. It is understood that the technology has been widely exported and in limited use in India.

ZERO EMISSION VEHICLES: A REVIEW

NOTE

THE MATERIAL IN THE SECTION ON ZERO EMISSION VEHICLES IS AN EXTRACT FROM REPORT OF THE ARB INDEPENDENT EXPERT PANEL. 13 APRIL 2007, PREPARED FOR STATE OF CALIFORNIA AIR RESOURCES BOARD, SACRAMENTO, CALIFORNIA

www.arb.ca.gov/msprog/zevprog/zevreview/zev_panel_report.pdf

Hydrogen fuel for Transportation and Power Generation Sector in India: The Rattan Tata Report (2005) [17]

Eleven years ago the Government of India had set up a steering group on hydrogen energy, set up by the Union Government under the chairmanship of the Tata group chief, projected an investment of Rs. 24,000 crores for creating infrastructure for hydrogen production, its storage, transportation and distribution, besides Rs. 1,000 crores for research, development and demonstration. Presenting the `National Hydrogen Energy Roadmap' to Minister for Non-Conventional Energy Sources Vilas Muttemwar, Mr. Tata said: ``The whole world, and certainly India, will face increasing shortage of hydrocarbon and so we have to look at alternative forms of energy... The document reflects the problems and attempts to define a road map."

However, he pointed out that a "whole lot of problems" existed relating to production, distribution and storage of energy from hydrogen. "The implementation is complex and expensive. But we have to find solutions to these," he said. The road map proposed two major initiatives — Green Initiative for Future Transport (GIFT) and Green Initiative for Power Generation (GIP) — as part of its proposals. GIFT aims at developing and demonstrating hydrogen-powered IC engine and fuel-cell based vehicles ranging from small two/three wheelers, cars/taxis, buses and vans through different phases of development. **If the road map was implemented, as many as one million hydrogen powered vehicles would run on the road.** GIP envisages developing and demonstrating hydrogen-powered IC engine/turbine and fuel cell-based decentralized power generating systems. The road map envisaged decentralized hydrogen-based power generation of about 1,000 MW aggregate capacity in the country by 2020. Members of the steering group included former ISRO Chairman K. Kasturirangan, Atomic Energy Commission Chairman Anil Kakodkar, and chairmen of Indian Oil Corporation and Bharat Heavy Electricals Ltd (BHEL). *Thus far not a single hydrogen fueled vehicle can be seen on Indian roads.*

In 2007, the State of California, USA commissioned another official study on Zero Emission Vehicles, that gave comprehensive details on the status of hydrogen fuel cells and the issues of hydrogen storage. This paper presents extracts from the US Report on the problems and promises of ZEV's. Since this technology is still in advanced R&D stage world over, it has been discussed as the ultimate, long term answer to the problem of air pollution due to vehicular traffic world over

Critical Technologies for ZERO EMISSION VEHICLES (ZEV) [10]

There are three main ZEV enabling technologies

(A) Energy Storage (batteries).
(B) Hydrogen Storage and
(C) Fuel Cells.

(A) Energy Storage Technologies (batteries).

Indian battery industry strategies and perspectives need to be ascertained in regard to three technologies

1. **Nickel Metal Hydride Batteries (NiMH**): High power NiMH technology for HEVs is now mature and mass manufactured in Japan in plants with capacities up to 500,000 systems annually. It is the conclusion of the Panel that high cost remains the greatest challenge for battery and HEV manufacturers, with an estimated cost (price to Original Equipment Manufacturers [OEMs]) of $2,000 for compact and $4,000 for a midsize HEV battery produced at a rate of 100,000 systems per year
2. **Lithium Ion Batteries (Li Ion):** High power Li Ion technology for HEVs appears close to commercialization in the view of the Panel. A variety of materials, manufacturing techniques and companies are competing to achieve the performance and cost goals for this established battery application which increases the probability of technical and market success. Importantly, for HEV applications Li Ion batteries have potentially lower cost than NiMH because they promise to deliver the required power with smaller capacities and lower specific cost
3. **ZEBRA Batteries** The ZEBRA (sodium-nickel chloride) battery technology has insufficient power density for HEV and PHEV applications but meets the technical requirements for small FPBEVs. The batteries have been successfully demonstrated in small European FPBEVs (Full Performance Battery Electric Vehicles), heavy duty vehicles and hybrid buses. The ZEBRA battery is likely to remain the lowest-cost advanced battery. However, the Panel has not seen any automobile manufacturer interest in the battery, probably due to a combination of **limited power density** and the implications of high temperature operation.

(B) Hydrogen Storage Systems Storing sufficient hydrogen on a vehicle to power it for adequate distance**, safely,** and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the automobile industry and its suppliers. A comprehensive review on Zero Emission Vehicles has been carried out in a Report of the ARB Independent Expert Panel on 13 April 2007, Prepared for State of California Air Resources Board, Sacramento, California. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one manufacturer identified it as the single greatest challenge.

Hydrogen Storage Systems In the near term, the dominant form of storing hydrogen onboard light vehicles will continue to be compressed hydrogen gas. With the exception of BMW, every other OEM contacted indicated that this was the only realistic short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. All the other OEMs preferred 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly provide almost 50% more range.

Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage is being demonstrated as workable but with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel. An important issue with any of the short term hydrogen storage options is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen.

Cost is another important issue, especially for the short term since none of the storage systems are produced in sufficient volumes to allow significant production economies of scale. While none of the OEMs gave specific current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to cost $10,000 or more each for both liquid and compressed gas storage.

Longer Term Outlook For the longer term, some of the alternative storage technologies being researched may prove to be effective. Both solid and liquid carriers are being researched with hydrogen “recharging “being carried out both onboard and off of the vehicle. There don’t appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire provided projections for complete system performance or costs. It appears to be too early to make reasonably accurate projections.

Conclusions of the Panel It is the conclusion of the Panel that on-board hydrogen storage is a major challenge for hydrogen fuel cell vehicles. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen gas storage which has problems providing sufficient vehicle range without excessive volume, weight, and cost. The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or design modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center “tunnel” is located and/or replacing rear coil springs with leaf springs to increase space available for hydrogen tanks.

Thus, depending on the type of vehicle and system efficiency, it seems likely that sufficient compressed hydrogen could be stored on a vehicle to provide a range in excess of 200 miles, perhaps reaching 300 miles or more. Liquid hydrogen storage technology appears to have advanced sufficiently that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range. However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. Assuming that at least 5 kg (165 KWh) of hydrogen will be needed to provide sufficient vehicle range, the cost would be $1650 even with the lowest TIAX tank cost estimate. For liquid storage, the cost would be even higher. There is little expectation that the cost of either of these systems will go much lower even with higher volumes.

The weight outlook is better than the cost outlook. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither TIAX nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, *the capacity to contain well over 6% hydrogen*. However, the remainder of the support system could have a huge effect on both cost and weight fraction.

(C) Fuel Cells A fuel cell is a device [18] that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. Fuel cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied Currently, according to Government of India’s Ministry of New and Renewable Energy, there are 18 academic and R&D organizations working in India on Fuel Cell technology.

This Government of India programme [19] focuses on development and demonstration of fuel cells, which produce electricity, water and heat through reaction between hydrogen and oxygen/air. Hydrogen is the primary fuel for fuel cells. Hydrogen for fuel cells can be produced by reformation of other fuels. It can also be produced from coal and biomass and by electrolysis of water. Renewable energy sources and nuclear energy can also be used for production of hydrogen. Because of their modular nature, fuel cells are ideally suited for distributed power generation. Small fuel cell power packs can be used for power generation by industrial and residential users. Fuel Cells are emerging as power sources for automobiles.

Achievements in India so far reported by its Ministry of Non-conventional and Renewable Energy are prototypes of PEMFCs and PAFCs developed, the application of fuel cells demonstrated for decentralised power generation, **a Fuel Cell (PEMFC)-battery hybrid van has been developed** in the country and has undergone field performance evaluation [19].