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Assessment of Real Driving Emissions from Vehicles Using Portable Emission Measurement Systems: A Systematic Review

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Abstract Vehicles contribute significant emissions in urban areas affecting the air quality of cities. Traditionally, vehicular emission factors (EFs) were developed based on measurements in the laboratory. However, studies indicate that the laboratory measurements are unrepresentative of real-world conditions. This study reviewed the literature on emission measurements of vehicles using Portable Emission Measurement Systems. The on-road emissions measurements were able to capture the emission characteristics during the micro events of real world driving scenarios which were not represented by standard vehicle emission measured at laboratory conditions. The current emission factors recommended by regulatory agencies like ARAI are laboratory based which were found to be under estimate the real world emissions. Compared to other measurement methods, such as dynamometer testing, on-board real time emission measurement provides detailed data that can be used to identify real-world estimates at micro scale events that significantly impact overall emissions. Accurate prediction of vehicular exhaust emissions is an important factor in predicting air quality in urban area which assists in policy and decision making process.

Keywords: *real driving emissions, emission factor, portable emission measurement systems*

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1. Introduction

Vehicular emissions contribute a significant amount of pollutants in urban areas, which lead to major concerns regarding health and well-being [1,2]. Many studies have attributed vehicular emissions as a major cause of diseases, including cardiovascular and pulmonary diseases. A higher number of deaths have been reported in recent years, due to the effect of urban air pollution, mainly affecting children and senior citizens. Moreover, the high population density in cities increases the number of people exposed to a high concentration of pollutants. This problem is more prominent in developing countries, where a significant proportion of urban commuters use walking, cycling, two-wheelers or buses for their work trips, thereby being exposed to a higher concentration of pollutants than those using personal cars.

Passenger car ownership has grown exponentially in recent years, particularly in developing countries such as India and China [3,4,5,6]. In India, the number of registered cars increased from 7.05 to 19.23 million during 2001-2011 and further to 28.61 million in 2015 (MoRTH, 2016). This has led to an increase in the travel distances, number of trips, congestion and pollutant emissions. Moreover, the price of diesel is lower than gasoline, which has led to substantial increase in the number of diesel cars. Diesel cars are known to cause higher emissions of gaseous pollutants, particulates, and black carbon, than gasoline cars. Many studies have attempted to quantify emissions of different pollutants from diesel passenger cars. However, all these studies have been conducted in laboratory conditions that fail to replicate real-world driving conditions.

Traffic on urban arterials in India is highly heterogeneous with pedestrians, cyclists, light and heavy motor vehicles sharing the same road space, with a predominantly higher proportion of two-wheelers in the total motorized traffic. This leads to frequent lane changing and haphazard driving, thereby inducing stop and-go conditions. In addition, the lack of lane discipline and roadside parking cause unique challenges to traffic flow. These factors lead to complex driving conditions which are difficult to capture in laboratory tests using existing standard driving cycles.

Driving cycle is a series of data points between speed versus time [7], speed versus distance [8], speed and gear selection as a function of time [9], or time vs gradient, in a specific region. There are two types of driving cycles that are developed - standard driving cycles and real world driving cycles. standard driving cycles are used the world over to enforce emission control norms while real world driving cycles are used to test and estimate field performance [10,11].

Thus, the main objective of our study is to characterize emissions from passenger cars plying on urban roads, using on-board measurement, and to develop emissions factors based on the measurements. The effect of different road conditions on emissions, effect of speed and acceleration on the emission rate will also be objective of this studied. This study contributes to the literature in the following aspects:

1. Literature review of various pollutants (CO, CO_2, HC, and NO_x etc.) from various class of vehicles (two-wheelers, three-wheelers, passenger cars (diesel, petrol and gasoline), and buses etc.) under heterogonous traffic condition.
2. This study is developed methodological framework to determine emission factors for vehicles in heterogonous traffic condition.

The article is organized into 5 sections. Section 2 discuss about the various pollutants from vehicles and their impact on human health. Section 3 compare regulatory framework to monitor real driving emission in world as well as in India. Section 4 presents the review of the literature relevant to this study. The last section describes the conclusions of this study and policy recommendation.

2. Vehicular Pollution

The automobile discovery satisfactorily combines a human desire for rapid transportation with the desire for independence and flexibility. However, rapid proliferation of motor vehicles, in both developed and developing country, poses a serious threat to the urban air quality. This chapter provides an overview of vehicular pollution scenario in metro cities including sources of vehicular pollution, types of vehicular pollutants and their health effects. The chapter also describes the principles of local air quality management, the ambient air quality standards for urban air sheds and overview of vehicular pollution models.

Air pollution from motor vehicles has become a major concern in rapidly urbanizing regions of the world because of increase in number of vehicles in use and the distance travelled by each vehicle each year [12]. Higher incomes, mobility, expansion of cities, and proliferation of employment centres have increased the demand for motorized transport, resulting into a disproportionately high concentration of vehicles in urban centres [13]. In last five decades worldwide, the number of vehicles is growing faster than the global population e.g. about 5 % per year compared to 2 %, for population. Over last 30 years, total global vehicular population has touched 700 million, which approximately consumes 34 % of total oil produced in the world [14,15].

2.1. Types of Vehicular Pollutants and Their Impact on Human Health

Common vehicular pollutants in urban environment are CO, NO_x, PM_{10}, SO_2, Volatile organic compounds (VOC's) and Lead (Pb). A substantial quantity of CO_2, which is a greenhouse gas, is also released. Pollutants emitted by motor vehicles have a number of adverse effects on human health. Inhalation is the main route of exposure to pollutants originating from motor vehicle emissions. Other exposure routes are - drinking water contamination, food contamination and absorption through skin. Exposure by inhalation directly affects respiratory, nervous and cardiovascular systems of humans, resulting in impaired pulmonary functions, sickness, and even death [16].

3. Regulatory Framework: Push towards Real-world Emissions Monitoring

As the vehicular emissions are a complex phenomenon, regulatory agencies around the world are constantly updating their standard procedures to provide more accurate results for exhaust emissions assessment. The existing emission factors were developed in the laboratory using dynamometer tests. These dynamometer tests were performed based on different driving cycles (standard vehicle operations) developed for different regions as shown in Table 2. Emission factors are a widely used method to assess transport emissions by relating pollutant emissions with vehicle activities such as traveled distance (g/km), fuel consumption (g/km), and energy consumption (g/kwh). Usually, emission factors depend on many variables such as model year, fuel type, vehicle size and vehicle type [17]. Emission factors were influences from both the start-up stage and the operation stage, respectively. It was found that during the start-up stage, the emission factors were mainly influenced by emission standards, fuel type, initial engine temperature and environmental temperature; during the operation stage, the emission factors were mainly influenced by driving speed, road properties and time properties [18].

Table 1. Effect of pollutants from vehicle exhaust on human health

Pollutants	Health effects
CO	Reduces delivery of oxygen to the body, which is particularly serious for those with cardiovascular diseases, causes impairment of function in healthy people.
NO_2	In high concentration, irritates lungs and lower resistance to respiratory infection; an important precursor to ozone and acid precipitation which can damage sensitive ecosystems.
VOC	Results in ozone, which can damage lungs tissue, reduces lung function, and causes irritation (these effects occur even at low levels in healthy people who engage in moderate exercise); also causes eco-system degradation, mainly through damaging foliage.
PM_{10}	In high concentration aggravates existing respiratory and cardiovascular disease, alters the immune system, can be carcinogenic, and causes lung damage.
SO_2	Major contributor to acid rain, degrades lung function and lower lung defences while aggravating existing respiratory disease.
Lead	Accumulates in the body and affects kidney, liver and nervous system; causes neurological impairments.

Table 2. Vehicular emission monitoring procedures and standards followed by various regulatory agencies across the globe

Region	Standard	Test Procedures	Driving Cycles
Europe	Euro 6	- Type 1 Exhaust emissions - Type II Idle CO - Type III Crankcase emissions - Type IV Evaporative emissions - Type V Durability - Type VI Low temperature emissions - Real world emissions (proposed)	NEDC cycle
USA	Federal legislation, California (CARB) standard	- Exhaust emission FTP-standards for an intermediate useful vehicle life - Exhaust emission FTP-standards for a full useful vehicle life - Exhaust emission SFTP-standards for a high load/high acceleration test - Exhaust emission SFTP-standards for a high temperature/air condition test - Low temperature CO-emission test - Low temperature NMHC-standards for gasoline vehicles	Complete FTP UDDS HW-cycle CARB unified cycle
Japan	Phase III	JC08 hot + JC08 cold chassis dynamometer exhaust emission testing	11-Mode cycle 10-15-Mode JC08
India	BSIV	Type I, Type II, Type III, Type IV similar to Europe	Indian driving cycle

In general, the driving cycles used in emissions quantification are composed of a unique vehicle profile of stops, starts, cruises, accelerations and decelerations. Since, the emission factors are developed based on these overall time averaged values of driving cycle, they were not representing real world driving behaviour [19,20,21]. The conventional emission factors were generally found to under predict the real world emissions as cited in various literature [22,23,24,25]. In addition, the standard driving cycles were not able to incorporate the short term events that were more prevailing in heterogeneous traffic conditions [26].

Emission factors were often widely used by regulatory agencies such as Environmental Protection Agency (EPA) in USA, Automotive Research Association of India (ARAI) in India for vehicular testing and certification. A recent EPA report on emission testing of diesel cars in US revealed that the manufacturers are inserting defeat devices which can give reduced emissions only during test conditions, while the real world emissions are found to be several times (35%) higher. Further these factors were generally used as inputs for various air quality prediction models which results in development of poor air quality management strategies [27,28].

In the recent global climate summit, India has pledged to improve the carbon emission intensity of its GDP by 33-35% by 2030 from the 2005 levels. It has also pledged to create an additional carbon sink of 2.5e3 billion tons of carbon dioxide (CO_2) equivalent through increasing forest and tree cover by 2030. The Indian oil ministry has also decided to skip Bharat Stage V (or Euro-V) and leapfrog directly to BS-VI (Euro-VI), which may include emission testing at real world conditions. In this context, accurate estimation of vehicle exhaust emissions through on board exhaust emissions measurement or real time emissions prediction models are necessary to prepare exhaust emission control strategies [29].

In order to control vehicular air pollution, regulatory agencies like United States Environmental Protection Agency (EPA) and Automotive Research Association of India (ARAI) have developed vehicular exhaust emission standards (ARAI, 2016). Emissions models like COPERT, MOVES, PHEM, and EMFAC have been widely used by various regulatory agencies to estimate emissions and to make control strategies [25]. In most of these models the emissions were measured in laboratory conditions using dynamometer by following a schedule according to different driving cycles. These driving cycles are not usually reflecting the driving behaviour of the real world conditions thereby adding considerable error into the emission estimation.

In India, still the emission standards are based upon dynamometer studies. Also, there are only a very few studies to measure emissions using on-board instrumentation. This type of real world emission testing is more relevant to Indian conditions mainly because the traffic is heterogeneous and very complex. Hence, there is a need to evaluate real world emissions of different types of vehicles depending upon varying road geometry, engine and traffic characteristics.

3.1. Bharat Stage-VI and Real Driving Emission

The term Real Driving Emissions (RDE) means what your vehicle emits in daily use on the road, not in a test environment. From 2020 onwards, passenger cars in India have to comply with the emission standard BS VI. As depicted in Figure 1, it will come into force nationwide, unlike its predecessor BS IV, which was introduced gradually throughout the country until 2017. The implementation is comparable with a transition from Euro 4 to Euro 6 and therefore requires a significant reduction of particulates and nitrogen oxides, (Figure 2). Therefore, in addition to a particulate filter, nitrogen oxide after treatment will also be required in the future.

According to the draft of BS VI (AIS-137), the type-1 test cycle will still be represented by the Modified Indian Driving Cycle (MIDC). It corresponds to the NEDC (New European Driving Cycle); however, it features a speed limitation of 90 km/h. In addition, the start of Real Driving Emissions (RDE) monitoring is planned for 2020, which will serve as a basis for the introduction of RDE Conformity Factors (CF) in April 2023. RDE India is also deduced from the European RDE packages, although some points are still to be defined.

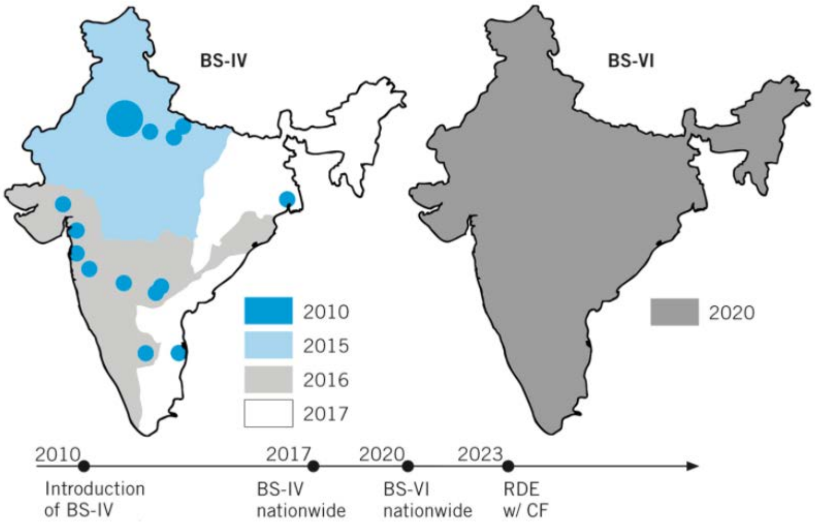

Figure 1. Introduction of BS-IV to BS-VI and RDE in India

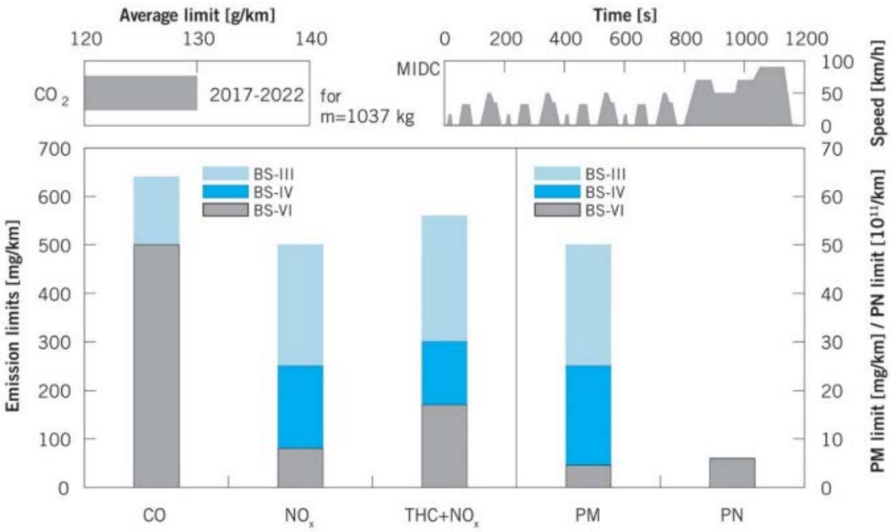

Figure 2. Emission limits of BS-III to BS-VI for diesel passenger cars (of vehicle category M: carrying passengers)

As a reason, the differences between the Indian and European overall conditions can be stated, which can mainly be found in traffic flow and cruising speed beside ambient temperature and geodetic situation. Traffic in India is generally characterized by a lower speed level.

This is due to congestion in the metropolises and a very coarse network of high-speed roads (expressways) with a speed limitation of 120 km/h and mostly charged access. The busy highways are usually limited at 80 km/h. In the problem zones concerning air quality, the urban areas, heavy and nose-to-tail traffic dominates, which exceeds European scenarios.

The typical operation at low speed is considered in the MIDC and moreover, in the planned RDE trip requirements (Figure 3) shows two provisional variants of obligatory trip parameters for the vehicle category M, which were announced in the AIS-137 draft.

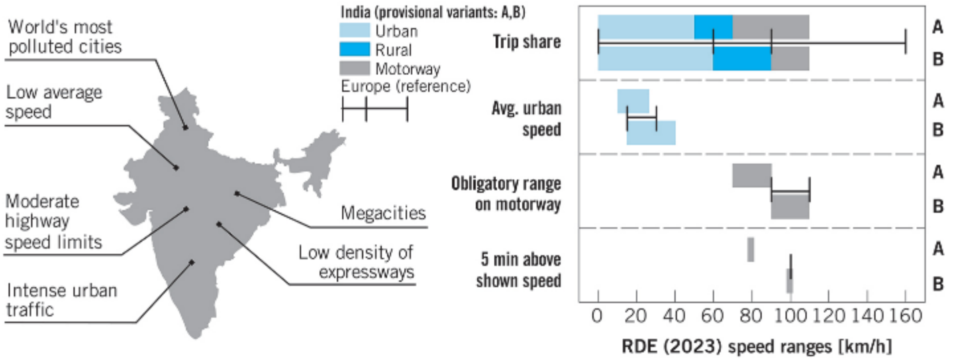

Figure 3. Characteristics of Indian traffic and two possible variants of implementation in RDE legislation

Variant A demands a lower speed level as B, which is closer to the European requisites. Both alternatives should, however, comply with a maximum speed of 110 km/h, which is distinctively below the European speed limit of 160 km/h.

4. Literature Review on Emission Measurements Using PEMS

Quantifying emissions from mobile sources, such as road vehicles, is a challenging task. This is because there are many factors that influence the emissions simultaneously and it is difficult to model all of them. Traditionally, in order to quantify emissions from vehicles, laboratory tests were conducted using standard driving cycles which represent the driving conditions on the road. However, the representativeness of the laboratory tests was found to be limited and hence, real-world emissions measurements were adopted using Portable Emission Measurement Systems (PEMS).

On-road emission monitoring of vehicles using PEMS has been adopted in several studies due to its reliability, accuracy, and ability to measure emissions under a variety of ambient and operating conditions. PEMS has been used to study emission characteristics of several different vehicle types in the real-world. Wyatt et al. [30] used PEMS to record CO_2 emissions from passenger cars in an urban road network, in order to determine the sensitivity of CO_2 emissions to road grade. Qu et al. [31] tested fourteen light-duty gasoline vehicles using PEMS in Tianjin, China, and determined emission factors for CO_2. Fu et al. [32] tested two Euro IV buses having Selective Catalytic Reduction with urea using PEMS, with an aim to assess NO_x emissions.

Lozhkina and Lozhkin [33] measured NOx emissions from diesel and gasoline passenger cars in St. Petersburg, Russia to determine the effect of speed, vehicle technology, and engine type on emissions. Diesel cars were found to emit significantly higher emissions compared to gasoline cars. Jaikumar et al. [20] monitored real world emission using portable emission measurement system of passenger cars on two very busy urban corridors having heterogeneous traffic flows. Results shows that Emissions at VSP modes under cruising speeds were 10-12 times less than idling (which is the mode used for emission standard certification), braking and accelerating conditions. They also found that the ANN model emissions was much higher than the ARAI and COPERT model and close to the on-board monitoring emissions. Jaikumar et al. [34] demonstrate the characteristics of real world, real time, on-road vehicular exhaust emission namely, carbon monoxide (CO), nitric oxide (NO), hydrocarbons (HC), and carbon dioxide (CO_2) emitted under heterogeneous traffic conditions. Results revealed that the driving cycle was dependent on the road geometry, with two lane mixed flow corridor having lot of short term events compared to that of arterial road. Vehicular emissions during idling and cruising were generally low compared to emissions during acceleration. They also founds that emissions were significantly dependent on short term events such as rapid acceleration and braking during a trip. Mahesh et al. [35] developed emission factors for diesel passenger cars using portal emission measurement system on urban arterials with heterogeneous traffic conditions in Chennai, India. The results show that the average carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NO_X) emission factors of the passenger cars were 1.28, 0.13, and 0.59 g/km, respectively. In addition, the measured EFs were influenced by the road type with higher emissions on roads with higher speeds and steeper accelerations. Mahesh et al. [36] quantify emissions of carbon monoxide (CO), hydrocarbons (HC), and nitric oxide (NO) from four typical motorcycles (MC 1, MC 2, MC 3, and MC 4) using real-world emission measurements and develop emission models. The real-world emission factors of CO for MC 1, MC 2, MC 3, and MC 4 were 12.3 times, 3.18 times, 9.71 times, and 5.84 times above the respective BS emission standard values. Also, the CO and [HC + NOX] emissions from a two-stroke motorcycle (MC 1) were higher than the four-stroke motorcycles. Adak et al. [37] developed real-world driving cycle for motorcycles, shared auto-rickshaws and passenger cars in Dhanbad, India. Developed DCs were used to calculate EFs for respective classes. Simulation of emission using real-world driving cycle reveals that shared auto-rickshaws have the highest emission factor among all vehicle classes under study hence it has greater contribution in local air quality degradation. Chiang et al. [38] developed real-world driving cycle for Taichung city of Taiwan and compared with Economic Commission for Europe (ECE) driving cycle of motorcycles. Results indicated the exhaust CO and HC emission factors of the TMDC driving cycle were significantly higher than those of the ECE. But the NOx emission factor of TMDC was lower than that of ECE. Gallus et al. [39] addresses the impact of different driving styles and route characteristics on on-road exhaust emissions. Gaseous emissions of two Diesel test vehicles (Euro-5 and Euro-6) were measured using a Portable Emission Measurement System (PEMS) on an RDE compliant test route. The PEMS results compared to normal driving, CO_2 increased by 20–40%, NOx emissions were higher by 50–255%. On the other hand, CO and HC emissions did not show a distinct separation of different driving styles. CO_2 and NO_x emissions linearly increases with road grade.

A summary of the literature review on measurement of emissions from vehicles is presented in Table 1. The major findings of these studies are also mentioned in Table 3. It is observed that most of the studies have been conducted in homogeneous traffic conditions. Heterogeneous traffic conditions consist of two-wheelers, passenger cars, auto rickshaws, trucks, and buses sharing the same road space. This leads to complex driving conditions that cause higher emissions [2,34]. Choudhary and Gokhale [40] found emissions to be sensitive to frequency and intensity of acceleration and deceleration caused by varying traffic conditions.

Table 3. Summary of literature review on emission measurements of vehicles using Portable Emission Measurement Systems

Citation	Study Area	Vehicle considered	Emission standard	Exhaust emission parameters	Experimental Condition	Model	Independent variable used in model	Major findings
Jaikumar et al. [34]	Chennai, India	Two-wheelers (2W), Three-wheelers (3W), Passenger cars, and Buses.	BS IV	CO, NO, HC and CO_2	Heterogeneous traffic	-	-	1. Emissions at two lane road with mixed flow were higher than that of the arterial roads. 2. Emissions during idling and cruising were generally low compared to emissions during acceleration 3. Standard emissions models like COPERT and CMEM grossly under predicting (30-200%) the real world emissions.
Jaikumar et al. [20]	Chennai, India	Diesel Passenger cars	BS IV	CO, HC and NO_X	Heterogeneous traffic	ANN Model	Speed, acceleration, engine speed, RPM, and VSP	1. Emissions at VSP modes under cruising speeds were 10-12 times less than idling, braking and accelerating conditions. 2. Developed ANN model emissions are close to the on-board monitoring results and much higher than the ARAI and COPERT models.
Mahesh et al. [35]	Chennai, India	Diesel Passenger cars	BS IV	CO, HC and NO_X	Heterogeneous traffic	-	-	EFs were influenced by the road type with higher emissions on roads with higher speeds and steeper accelerations.
Mahesh et al. [36]	Chennai, India	Motorcycles	BS II and BS III	CO, HC and NO_X	Heterogeneous traffic	Polynomial regression	Speed	CO emission from motorcycles is significantly higher than the emission standards and HC + NOx emission factors for two-stroke motorcycle were higher than the four-stroke motorcycles.
Adak et al. [37]	Dhanbad, India	2-W (4S), shared auto-rickshaws (diesel) and cars (diesel)	BS II	CO, HC and NO_X	Heterogeneous traffic	-	-	Shared auto-rickshaws have the highest emission factor w.r.t. motorcycle and passenger cars.

5. Conclusion and Policy Recommendations

The cities in developing countries are facing serious challenge because of vehicular pollution. The reason may be attributed to the increase in road infrastructure and exponential increase in number of vehicles. The current emission factors recommended by regulatory agencies like ARAI are laboratory based which were found to be under estimate the real world emissions. Compared to other measurement methods, such as dynamometer testing and remote sensing, on-board real time emission measurement provides detailed data that can be used to identify real-world estimates at micro scale events that significantly impact overall emissions.

Pollutant emissions from diesel passenger cars has been a much-debated subject over the past few years, prompting attention on in-use testing of vehicles using PEMS. However, India is yet to adopt in-use emission testing of vehicles. Based on the literature, the dynamometer test and different driving cycle did not reflect the real-world vehicle exhaust emission. Therefore, the development of a localized driving cycle (for various class of vehicles) and an on-board exhaust analyzer is important for the estimation of vehicle pollution and other assessment of mobile source pollution control programs. Accurate prediction of vehicular exhaust emissions is an important factor in predicting air quality in urban area which assists in policy and decision making process.

Despite experiencing a phenomenal growth in the number of motor vehicles as compared with developed nations, Indian emission control policies are not stringent enough to effectively monitor and control mobile emissions. Due to the one-time taxation of personal vehicles during purchase, many older vehicles continue to ply without any restrictions. Moreover, the pollution under control (PUC) checks, which are mandatory in most cities, fail to achieve the desired results as the testing facilities lack trained manpower and accurate instrumentation. In addition, non-uniformity of emission standards across the country leads to a shift in older and more polluting vehicles to smaller cities, thereby leading to poor air quality.

The emission standards prescribed by the Automotive Research Association of India (ARAI) are based on laboratory testing of vehicles, and there has been limited emphasis on real-world emissions monitoring. However, the Diesel gate incident has prompted India to plan for implementing real-world testing (proposed from April 2023), once the Bharat Stage VI emission norms are in place from April 2020. With proper implementation, this would be instrumental in controlling emissions from motor vehicles.

Finally, a combination of policy decisions, including congesting pricing, introduction of electric vehicles, encouraging public and active transport, and carpooling, would be necessary to achieve a drastic reduction in emissions. Several steps have been taken recently in this regard, such as the odd-even policy in the capital city of Delhi and the introduction of app-based taxi services. Furthermore, the government proposes to achieve 100% electric mobility by 2030. Although there are several challenges, such as poor charging infrastructure and high initial cost of electric vehicles, this could be a revolutionary step towards reducing dependence on fossil fuels and improving air quality in cities.

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