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STUDY OF TEMPERATURE PROFILE IN AUTOMOTIVE EXHAUST SYSTEMS FOR RETROFITTING CATALYTIC CONVERTERS

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ABSTRACT
Retrofitting catalytic converters into existing exhaust emission systems can be one option of emission control from vehicles, where it was not incorporated by the manufacturer. A retrofitted converter needs to be operating at proper temperature, creating permissible pressure drop and the amount of pollutants produced by the engine should be within its maximum cleaning capacity. The flow rate and temperature profile of the burnt gases passing through the exhaust system is required to determine the most effective location for catalytic converter placement. Temperature of exhaust gases confined inside the pipes are difficult to measure from outside making it a rare practice in Bangladesh. This experimental work is aimed to develop a simple method for estimating the temperature profiles of the exhaust gases from surface temperatures of exhaust piping. It could be used for determining the suitable thermal location for retrofitting a catalytic converter is such vehicles, and to check whether the availability of space or effect on ground clearance makes such a modification practically feasible.

Keywords: Automotive exhaust, Exhaust pipe, Temperature profile, Retrofitting, Catalytic converter, Data acquisition system.

1. INTRODUCTION
The increasingly greater concerns regarding environmental pollution created from automotive emissions, is leading to more stringent emission control requirements world wide. This has forced the auto-manufacturers to develop and use various pre-engine, in-engine and post-engine technologies to reduce pollution from automotive engines. The catalytic converter is one of such post-engine devices used to convert the harmful gases like CO, NOx and unburned hydrocarbon emitted from a gasoline engine in to less harmful forms like CO_2, N_2 and H_2O. While catalytic converters are increasingly becoming an essential feature in modern automobiles run by a gasoline engine, still many vehicle models, especially those used in developing countries, do not have this feature incorporated in the manufacturer's design. Retrofitting of catalytic converters into existing exhaust emission systems can be one option of emission control from such vehicles. A catalytic converter retrofitted into an existing exhaust system needs to fulfill a number of basic requirements in order to provide the desired improvement to the engine exhaust. It needs to be operating at the proper temperature, the pressure drop created by its inclusion in the exhaust system has to be within the limits permitted by the engine and the amount of undesirable pollutants produced by the engine should be within the maximum cleaning capacity of the catalytic converter to be fitted. In order to establish the feasibility of such a modification, there is the need to assess the proper thermal location for retrofitting a catalytic converter in an existing automotive exhaust system, as well as checking the availability of space required and possible effects on vehicle ground clearance.

The flow rate and temperature profile of the burnt gases passing through the exhaust system is required to determine the most effective zone for placement of a catalytic converter. As the exhaust gases are confined inside the pipes it is difficult to measure its temperature from outside. Hence such assessments are rarely practiced during retrofitting in Bangladesh. This experimental work is aimed to develop a simple method for estimating the temperature profiles of the exhaust gases with reasonable accuracy.

2. EFFECT OF TEMPERATURE ON CATALYTIC CONVERTER PERFORMANCE
A catalytic converter (CC) is a post-engine emission control device used in spark ignition engines. It is fitted in the exhaust line and reduces the emission generated by the engine, before being exhausted to the atmosphere. It has no moving parts and inside a converter exhaust gases take part in chemical reactions, in presence of catalyst materials. CC converts polluting gases like CO, NO_x and unburned Hydro-Carbon (HC), into CO_2, N_2 and H_2O, which are not pollutants. The reactions only take place in

presence of catalyst materials like – Platinum, Rhodium and/or Palladium. In a catalytic converter, large surface area is provided for the chemical reaction to take place and a very small amount of precious catalyst material is distributed throughout the structure in an ultra-thin layer. Catalytic reactions are generally exothermic, so heat-shields and temperature withstanding materials need to be used for its construction. Figure-1 shows the typical placement of a catalytic converter in an automobile.

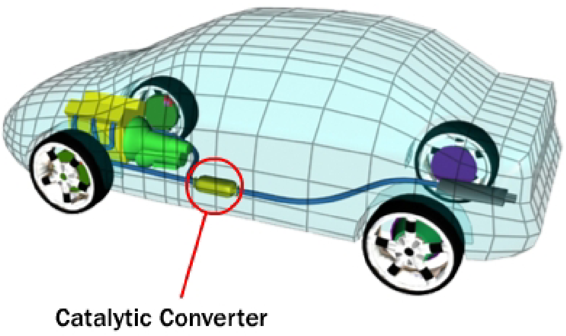


Fig 1. Location of Catalytic Converter in a typical car.

Generally speaking, catalytic converters are good post-engine emission controlling devices capable of achieving more than 90% reduction of the emissions generated by a well tuned modern engine [1]. However, it should be noted that, this level of performance from a catalytic converter can be only expected, when a number of prerequisites are met. For a catalytic converter to function effectively, it is essential that the proper chemistry and operating temperature be present. These factors are critical to consider when retrofitting a converter on a vehicle which was not originally designed or equipped for its use. These generally include vehicles produced till late 80's in Japan and European countries and till early 80's in USA, many of which are still used in developing countries [2].

Catalytic converters operate under complicated highly dynamic conditions and catalytic reactions occur at typical exhaust gas temperatures leaving the cylinder. This in warmed-up gasoline engines, can vary from 300°C to 400°C during idle, raising even up to about 1000°C, depending on the driving conditions. Different engines possess different warm-up characteristics from cold-start as well. These catalytic reactions depend on the temperature and the composition of the exhaust gas. The activity of the catalyst as a function of its temperature is a critical feature of the catalyst's performance and is affected by a number of exothermic reactions. When the engine is started, the exhaust gas gradually heats up to initiate the catalytic reactions, once the 'light-off'(typically reaching 50% conversion efficiency) temperature is reached. NOx efficiency remains very high regardless of temperature. However, CO and HC efficiency varies significantly with temperature. As temperature increases CO oxidation reactions typically start first, followed then by HC oxidation[3,4]. Hence the placement of the converter in the exhaust system relative to the engine is important to ensure that the exhaust temperature is sufficient for the operating range of the catalyst as suggested from figure 2a. On the other hand, if the converter is too close to the engine, it may be exposed to excessive temperature damaging the catalyst [5].

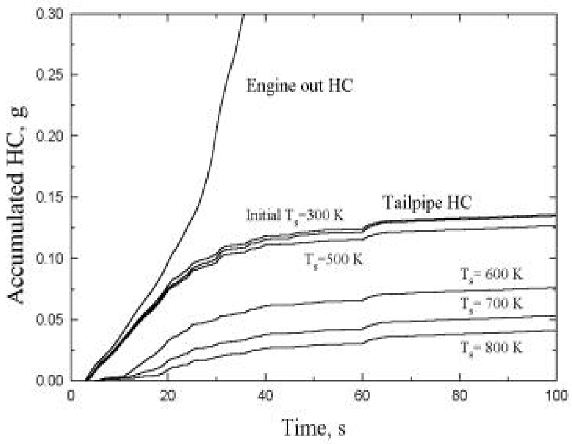


Fig 2a. Effect on HC emission in a FTP cycle as a function of CC start temperature [6].

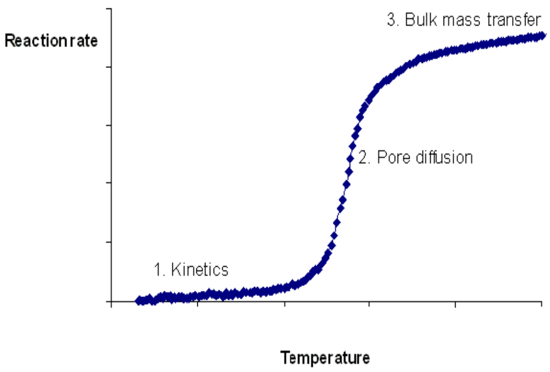


Fig 2b. Typical conversion regimes for controlling CC conversion rate as a function of temperature [7].

Figure 2b presents, a typical activity plot. At low temperatures, the reaction rate is so small that no conversion is reached over the catalyst. In this stage, the reaction kinetics is the controlling factor for the overall reaction rate, whereas in the second stage, the conversion is limited by the pore diffusion in the wash-coat. Catalyst light-off typically occurs in this temperature range. The high temperature region corresponds to bulk mass transfer between the gas phase and wash-coat [7].

Thermocouples(TC) are still the most reliable way of exhaust gas temperature measurement, if exposed to the gas. Unfortunately this is not very convenient to measure the temperature of automotive exhaust passing through the piping. Resistance temperature detectors(RTD) in addition may cause significant disturbances to exhaust flow. To overcome these limitations a number of other techniques are being employed [8]. Infra-Red(IR) sensors are being used to estimate internal exhaust temperature from pipe surface IR measurements [9], systems with high accuracy are expensive. High-temperature stable air borne ultrasonic sensors have been successfully used for exhaust gas temperature estimation, but the devices presently can measure only up to 400°C, above which a water cooling system is needed to protect itself. The temperature measured also varies in accuracy as the pulsation frequency of the exhaust gases from the engine changes[10]. Metal-insulator-silicon carbide devices have been used for gas sensing in automotive exhausts, because the large band gap of SiC allows high temperature operation up to 1200°K in chemically reactive environments [11]. This method also has the limitation that the gas needs to be in contact with the device.

3. EXPERMENTAL SETUP AND METHODOGY

The exhaust gas flow from the cylinders of piston engines is a highly complicated dynamic process. The temperature profile of a typical automotive exhaust system (Toyota LiteACE, 1.3 liter 97x93mm SI, 4-cylinder, Inline, Carburetor fitted, Naturally aspirated, Water cooled, 25 kW, 700–3200 rpm) was measured at the outer surface of the pipes as well as the gases inside at the corresponding locations. A parallel-port PC based data acquisition systems (PICO,TC-08) was used for measurement and recording of temperature across the vehicle exhaust piping. Type-K thermocouples were used as sensors for measuring temperatures. Table-1 shows the general specification of TC-08. Along the exhaust line at a number of locations (limited by the maximum number of channels available with TC-08) thermocouples were installed in pairs one inserted inside and one clamped at the exhaust pipe surface. Using the data acquisition system allowed simultaneous recording of data of the exhaust gases at different locations which reaches a quasi-steady state in reality with the fluctuation of pulsating exhaust gas flows. The temperature profiles of typical piping surface and the burnt gases inside were recorded from engine starting condition, through the transient period of engine warm-up, until nearly steady states were reached.

Table 1: Specification of TC-08 data acquisition system.

Thermocouple types	B, E, J, K, N, R, S, T
Temperature range (Type-K)	-270 C to 1370 C
Voltage range	±60mV
Number of input channels	8
A/D resolution	12 bit
Sampling Rate	1 kS/sec
Conversion time -per active channel	200ms
Conversion time-cold junction compensation	200ms
Accuracy	±0.3% and ±0.5 C
Common mode range	±4V
Over voltage protection	±10V
Input impedance	2M Ohm
Input connectors	8 x miniature thermocouple
Output connector	9 way female D25-type to computer serial port
Power requirements	Parallel port, No separate supply required

This procedure was repeated for engine idling under no-load condition and accelerating to a certain speed. Pairs of thermocouples were externally clamped along the pipe surface and drilled through the corresponding locations. Figure-3 shows a photograph of the experimental setup, with the vehicle body structure removed. From the temperature data a generalised relationship between the inside gas temperature to the surface temperature of a typical automotive exhaust system was established. This equation was used to estimate the exhaust gas temperatures in four vehicle models, widely used in Dhaka, from surface temperature measurements. The detail geometry of the exhaust flow path for each vehicle was recorded. This allowed to readily estimate the temperature profile of the exhaust gases without damaging the exhaust pipes.

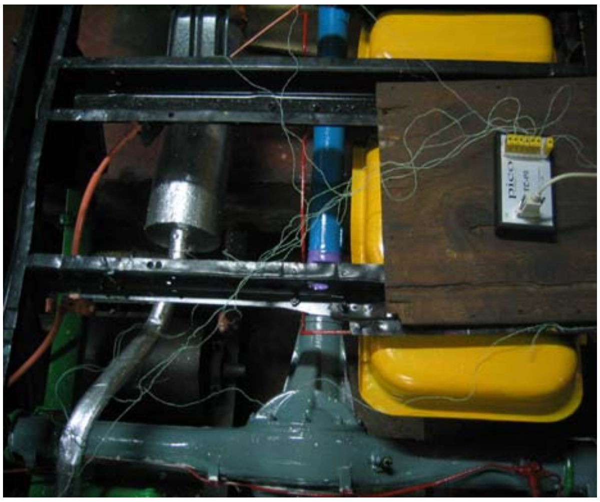


Fig 3. Experimental setup with the vehicle body structure removed.

4. DEVELOPMENT OF THE EQUATION

The temperature of the pairs of thermocouple connectors were recorded after initial warm-up and reaching a steady state for the Toyota LiteACE vehicle. Figure-4a shows the location of thermocouple pairs installed on the exhaust line. Due to the limitation of maximum 8 channels available with TC-08, this had to be limited with 4 locations. Repetition of runs with shifted locations generated similar pattern of results. The engine was run at idle condition (about 700 rpm) and a free accelerated condition (about 2000 rpm). Figure 4b and 4c shows the relationship between the surface and exhaust gas temperatures at idling and accelerated conditions respectively. In idle condition the variation of temperatures were fairly consistent between successive runs. At accelerated engine condition the exhaust gas temperatures varied with a wider band, at different runs. To reduce the error level the comparisons were made involving a large number of runs. Two appropriate equations were estimated for idling and accelerated conditions of the engine. Figure 5 shows the comparison of the estimated and measured temperatures for almost identical runs along the exhaust line of the test vehicle for both idling and accelerated engine speeds. In this stage first eight thermocouples were connected on pipe surface and then in another nearly identical run the exhaust temperatures at the same locations were measured.

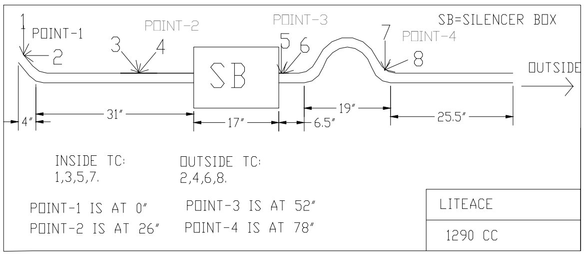


Fig 4(a) . Location of TC pairs along exhaust length

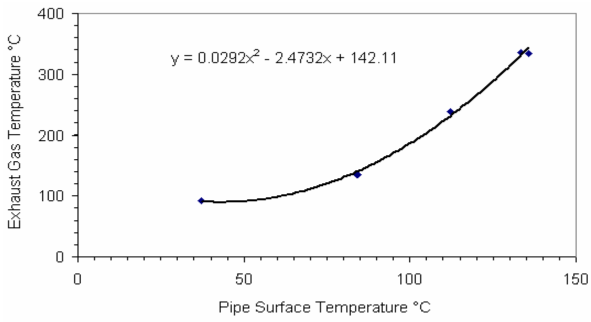


Fig 4(b). Variation of temperatures, engine idling

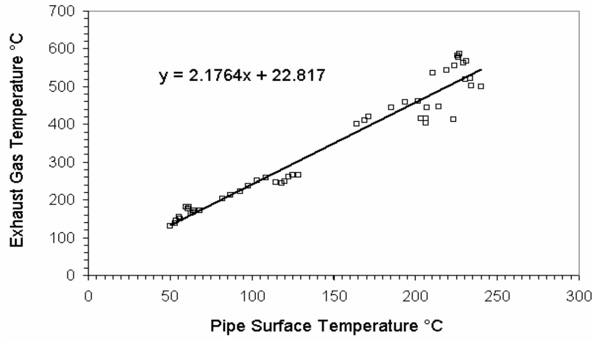


Fig 4(c). Variation of temp., engine accelerated

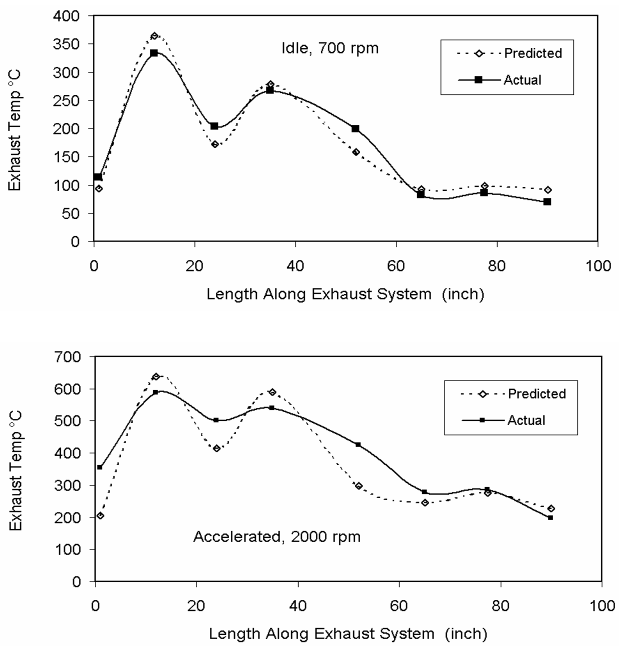


Fig 5. Verification of prediction with similar runs

The comparison shows that with the engine idling at 700 rpm the exhaust temperature distribution predicted from equation and experimental measurements of identical runs were similar, the maximum variations being within ±10%. The variations in exhaust temperatures for accelerated condition were found to be wider, ranging up to ±25%. However considering the fact that at accelerated speeds the variation of actual flow conditions is expected to vary more between similar runs, may contribute to this increase in the temperature variations.

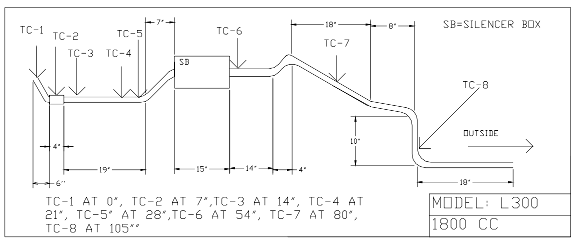
Two interesting features in the typical pattern of temperature distribution in exhaust line were also noticeable from the study. Along the flow path generally the exhaust temperature decreases further away from the engine, but the rate is reduced or even temperature increase could be observed in locations were the silencer box or sharper tube bends were present. In such places the stagnation time is increased, which may allow more heat to be transferred to the surface, resulting in overshooting of predicted temperatures. The increased stay period may also allow some after-burning or oxidation, which may even raise the exhaust temperature at such locations. Very near to the exhaust manifolds a noticeable temperature drop was observed, this is created by the sudden expansion of exhaust gases as they come out of the cylinder at a relatively higher pressure. As the gas moves a short distance it meets the bulk of fluid in the exhaust line and quickly recovers its temperature as the kinetic energy is expended [12]. Contact thermal resistance of the copper clamps and radiation heat losses were assumed to be negligible.

5. APPLICATION IN DIFFERENT MODELS

Four different models were tested as an application of the method developed, for estimation of inline exhaust temperatures, using surface temperature measurements. The carburetor fitted vehicle models were chosen for being some of the most common vehicles used in Dhaka city, which already did not incorporate a standard catalytic converter in their design. Their engine specifications are stated below. Estimations were made at both idle and an accelerated conditions.

Model	Specifications
MITSUBISHI L300	1800 cc, 4 cyln
TOYOTA EE80-FEKDS	1300 cc, 4 cyln
MAZDA GFD W3W	1300 cc, 4 cyln
TOYOTA EE100-RAEMN3	1300 cc, 4 cyln

Model: MITSUBISHI L300



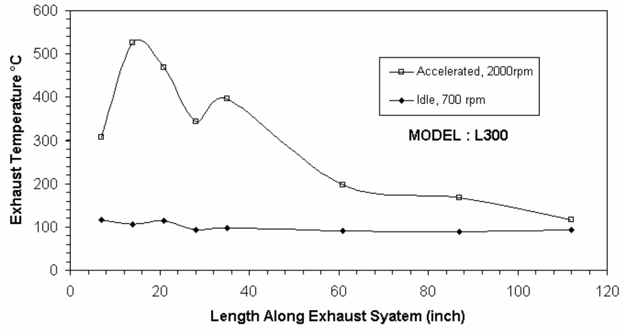


Fig 6(a). Exhaust temperature estimates for vehicle model – MITSUBISHI L300

Model :TOYOTA EE 80-FEKDS

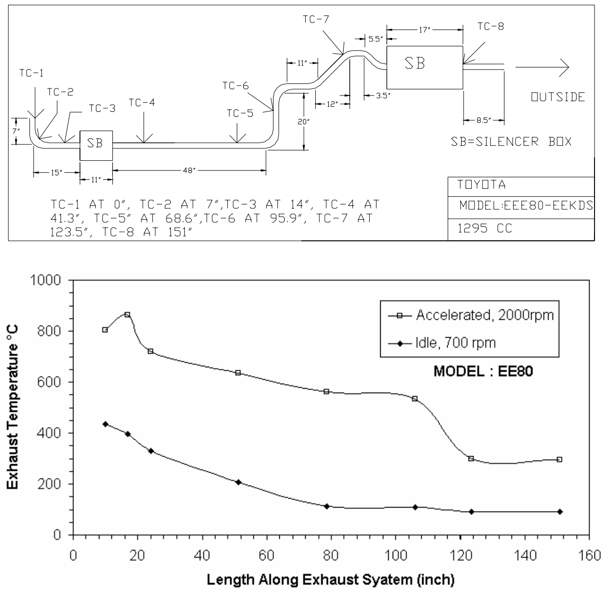


Fig 6(b). Exhaust temperature estimates for vehicle model – TOYOTA EE 80-FEKDS

Model : MAZDA GFDW3W

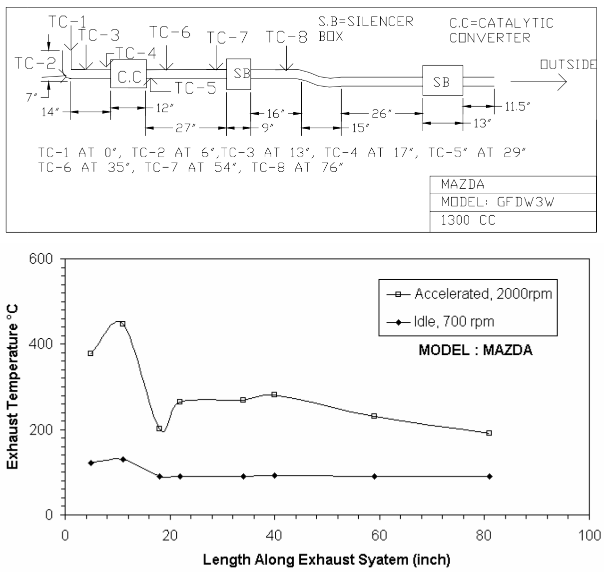


Fig 6(c). Exhaust temperature estimates for vehicle model – MAZDA GFDW3W

Model: TOYOTA EE100RAEMN3

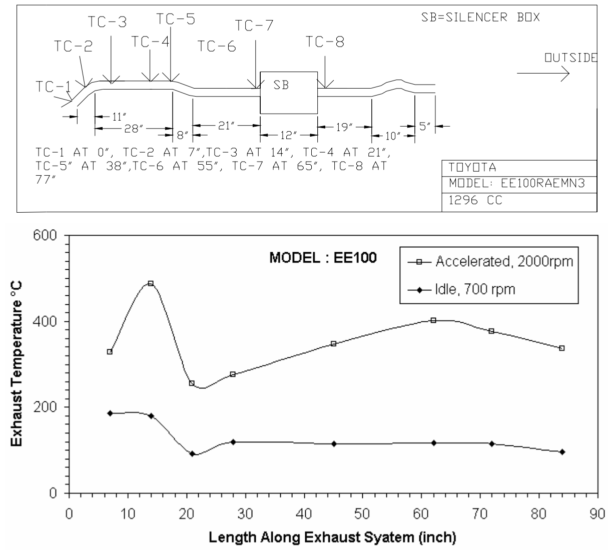


Fig 6(d). Exhaust temperature estimates for vehicle model – TOYOTA EE100RAEMN3

The surface temperature readings were taken in nearly stable conditions after initial warm-up. The inline temperature distribution estimated for the four vehicles for idling and an accelerated speed are plotted in figure 6a-6d. The idling speed of all of the vehicles were found to be varying between 650-750 rpm. All the results showed the general trend of decrease in exhaust temperatures in the smoother parts of the exhaust path. Near obstacles like silencer boxes, the flow resistance increased resulting in variation or even local increase of exhaust temperature. Models like Toyota EE80 and Mazda GDF had two separate silencer boxes (generally suppressing different frequency ranges), while Toyota EE100 and Mitsubishi L300 models were supported by single composite boxes. All the vehicles were fitted with typical exhaust piping with the outside diameter ranging from 40-45 mm. Since the vehicles were in service for some time, the inside condition of the silencer boxes also may vary which may affect the resistance to exhaust gas flow to some extent.

The exhaust temperatures for idling conditions were much lower compared to accelerated conditions. Since catalytic converters need a light-off temperature of at least 250°C, the use of a typical catalytic converter may not have much improvement, unless placed very near to the engine which may be not possible due to physical space constraints. In modern engines, the system mainly relies on electronic fuel metering and the lambda-sensor, or a small pre-catalytic device very near the engine exhaust manifold to achieve lower pollution at idling. The Mazda GDF model was found to be fitted with such a catalytic device, generally used to reduce pollution at engine idling. At accelerated conditions all the models had the prospect of reducing exhaust pollution, if fitted with a catalytic converter in the initial portion of the exhaust system. The convenient zones were found around 60–80 inches for L300, 40-80 for EE80, 20-30 for Mazda and 40-70 for EE100, away from the exhaust manifold. There was not enough physical space available to place a standard catalytic converter on the Mazda GDF in the effective thermal zone. Incorporating catalytic converters generally would decrease the distance between ground and the silencer system, but this may or may not have effect on the minimum ground clearance, based on its location.

6. CONCLUSIONS

Assessment of the temperature distribution in an automotive exhaust line is necessary to ensure the effective use of a retrofitted catalytic converter, which is a rare practice in Bangladesh. A simple, non-destructive method of estimating the temperature of in-line exhaust gas from pipe surface temperature measurements was developed. The estimated values were found to be within 10% for engines under idling conditions and 25% at an accelerated speed of 2000rpm. The procedure was tested on four different vehicles, for in-line exhaust gas temperature estimation. The measurements could identify the thermally suitable locations to retrofit catalytic converters. Test results also revealed a retrofit in many of the vehicles may not be effective for emission reduction under idling conditions, which is an important concern in Dhaka city with lot of stagnant traffic-jams.

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