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Assessment of Manual, Automatic and Continuously Variable Transmission Powertrains for Gasoline Engine Powered Midsize Saloon Vehicle

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ABSTRACT:

Modern integrated powertrains allow great scope for improvements in driveability, emissions and fuel consumption by optimizing the engine speed and load selection to deliver the demanded power. The aim of this study is to assess the exhaust emissions, road performance, road acceleration and fuel consumption of gasoline engine powered vehicle. The proposed emission index and fuel consumption rate are verified through chassis dynamometer tests using the urban part of European drive cycle (ECE-15). A midsize saloon vehicle equipped with an integrated gasoline engine with manual transmission (MT), automatic transmission (AT) and continuously variable transmission (CVT) powertrains. The results indicate that most of the carbon monoxide, carbon dioxide and unburned hydrocarbons emission, driveability and fuel consumption rate were improved for the CVT powertrains.

KEYWORDS:

Gasoline engine; Continuously variable transmissions; Fuel consumption; Driveability; Emissions

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ACRONYMS & NOMENCLATURE:

MT	*Manual Transmission*
AT	*Automatic Transmission*
CVT	*Continuously Variable Transmission*
CO	*Carbon Monoxide*
CO_2	*Carbon Dioxide*
HC	*Hydrocarbons*
FCR	*Fuel consumption rate (g/s)*
EI	*Emission Index*
UDC	*Urban Driving Cycle*
NEDC	*New European Driving Cycle*
φ	*Fuel/air equivalence ratio*
$(X)_{MT}$	*Value for manual transmission*
$(X)_{AT,CVT}$	*Value for automatic or CVT*
PFMT	*Percentage Factor for various transmissions as compared with MT*

1. Introduction

In the current environmental and political framework, exhaust emissions are fundamental considerations in the development of any powertrain control strategy. Despite this there has been comparatively little published work concerning the optimization of exhaust emissions. Additionally, fuel economy must not be neglected as it will remain as a crucial measure of vehicle efficiency. Extending the earlier work reported, the economy line concept includes an evaluation of exhaust emissions. The major flaw of the economy line approach is the failure to optimize exhaust emissions performance similar to ideal operating line (IOL) approach. When optimizing for a single outcome, such as minimum fuel consumption, a true optimum line is simply generated. If this process is repeated for each of the pollutants a different line will be generated in each case owing to their differing formation mechanisms. Thus, it is not possible to arrive at a globally optimum line. To resolve this difficulty the regulated exhaust emissions are combined with fuel economy in a weighted sum, which is minimized across the operating power range of the engine [1-3].

Vehicle powertrains are becoming increasingly complex as the scope offered to improve vehicle performance, economy and emissions is explored. Considerable benefit may be derived from operating the engine and transmission in an integrated manner, using a single controller to interpret the driver’s wish and accordingly instruct the engine and transmission controllers. Crucial to the success of such system are the basic specification of major components and the design of overall powertrain control strategy. Continuously variable transmission (CVT) can provide a better performance of vehicle concerning the fuel consumption and driveability [4-5]. Deacon et al [6] implemented artificial intelligence and more traditional and intuitive methods for an integrated diesel CVT powertrain and compared with an existing controller and equivalent manual transmission (MT) powertrain. Chassis dynamometer results show the newly designed controller strategies to have significant impact on vehicle exhaust emissions, while the structure of the software allows the controller action to be highly tuneable and flexible to balance the vehicle driveability requirements with economy and emissions targets.

One of the fundamental concepts in the integrated driveline control is the ideal operating point (IOP) which is defined as the engine speed and load which delivers the desired power whilst producing the lowest level of undesirable emissions. A locus of IOPs may be drawn across the engine speed/load map and referred to as an IOL. The undesirable emissions are more wide ranging than the traditional concern relating to CO_2 (directly analogous to fuel consumption). The aim was to balance drivability, fuel economy and emissions considerations. Each controller was tested three times using different IOLs for best brake specific fuel economy (BSFC), minimum Nitrogen Oxide (NO_x) and a mixed line for minimum Hydrocarbon (HC) [7]. Carbone et al [8] utilized CVT with infinite ratio range for automatic gear change without the need of the friction clutch. The performance of a mid passenger car provided with infinitely variable transmission (IVT) was studied. Vehicle's fuel consumption was evaluated by means of a simulation model with the hypothesis to consider the value of IVT's ratio speed that minimizes the specific fuel consumption. The IVT's performance was compared with traditional ones. A comprehensive emissions model was developed and integrated with a variety of transportation models by Schulz et al [9]. Second-by-second engine-out and tail pipe emissions data were collected on 340 light duty vehicles, tested under "as is" conditions. Variability in emissions of CO_2, CO, HC and NO_x were observed over various driving modes. An initial statistical analysis and model validation using bootstrap validation methods were summarized. The bootstrap methodology was shown to be a valuable tool during model development.

In this work, the influence of various driving cycles on vehicle exhaust emissions and fuel consumption rate (FCR) of a gasoline midsize saloon vehicle was investigated based on the measurements obtained by driving it on a standard chassis dynamometer. The tests were carried out for urban part of the European standard driving cycle (ECE-15) for the vehicle equipped with an integrated gasoline engine with MT, automatic transmission (AT) and CVT powertrains. An estimation of emission index (EI) and FCR from the exhaust emissions based on well established formulae is provided and its effectiveness is verified through tests.

2. Analysis models

For a given vehicle category and its speed and acceleration time history, the engine emissions model can predict the corresponding FCR and emissions time history [10]. The emissions index EI_i for content i is defined as the ratio of engine-out emission rate of content i as EO_i in g/s and FCR in (g/s) using [10-12]:

$$EI_i = EO_i / FCR \qquad (1)$$

Where i denotes generic emission content such as CO_2, CO and HC. Vehicle's CO and HC pollutant emissions are investigated using an emission (pollution) index (EI) as:

$$EI = \left(\frac{(CO/1) + (HC/0.1)}{2} \right) \qquad (2)$$

In which the average of each pollutant is in g/km unit. The constants 1 for CO and 0.1 for HC are used to make the EI dimensionless. Given the second-by-second speed and acceleration, this can predict the corresponding second-by-second EI [13-14].

FCR is calculated using the following carbon balance formula [14]:

$$FCR = \left(\frac{CO_2}{44} + \frac{CO}{28} \right) + [12 + 1.85] + HC \qquad (3)$$

Where 44, 28, 12 and 1 are the molecular weights of CO_2, CO, C and H respectively. Constant 1.85 is the approximate number of molecules of hydrogen per molecule of carbon in the fuel. CO_2, CO and HC are the measured engine-out emission rates. This formula derives the equivalent mass of hydrocarbon from the carbon balance of the emissions measurements.

The powertrain transmissions assessment is undertaken by calculating the percentage factor (PFMT, %) for various transmissions as compared with MT. These transmissions are compared directly with MT in terms of the vehicle power, EI, fuel economy and acceleration performance using:

$$PFMT, (\%) = \frac{(X)_{MT} - (X)_{AT,CVT}}{(X)_{MT}} \qquad (4)$$

Where: $(X)_{MT}$ and $(X)_{AT,CVT}$ is the value for MT and, value for AT or CVT powertrain respectively.

3. Test setup and instrumentation

The experimental tests were carried out using in-use midsize saloon vehicle Mitsubishi Lancer. Its maximum power is 122 HP at 4800 rpm and maximum torque 167 Nm at 3600 rpm. The original configuration of vehicle had MT powertrain. The MT was replaced by either AT or CVT with the necessary fixation accessories. The tests were performed over standard driving cycle executed on chassis dynamometer. The specifications of the transmissions are listed in Table 1. The vehicle was tested over the New European Driving Cycle (NEDC). This cycle is conducted immediately after the urban cycle and consists of half steady-speed driving with accelerations, decelerations and some idling. NEDC consists of ECE15 and EUDC which correspond to urban and highway driving conditions in order. ECE15 simulates an average speed of 18.9 km/h and a maximum speed of 60 km/h. The entire cycle includes 4 repeats of 780 seconds low speed urban cycle to obtain an adequate driving distance as shown in Fig. 1. The EUDC simulates an average speed of 63 km/h and a maximum speed of 120 km/h. In this study, only part of urban cycle with the duration of 190 seconds is used and its mean parameters are given in Table 2.

Table 1: Specifications of transmission types

Gear shift	Transmission ratio		
	MT	AT	CVT
1st	2.857	3.655	Infinite number of shifts between pulley ratio 2.349: 0.394
2nd	1.950	2.368	
3rd	1.444	1.754	
4th	1.096	1.322	
5th	0.761	0.775	
Reverse	2.892	4.011	5.69

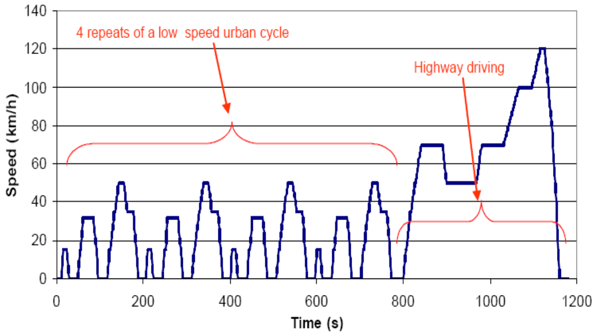

Fig. 1: European driving cycle ECE-15

Table 2: Mean parameters of ECE15 driving cycle - first part

Parameters	Values	Units
Total time	190	Sec.
Driving time	150	Sec.
Total distance	994	m
Average driving speed	23.8	Km/h
Average acceleration	0.348	m/s^2
Number of acceleration	3	--
Average deceleration	-0.393	m/s^2
Root mean square of acceleration	0.18	m/s^2

The chassis dynamometer type SAXON TL-80 simulates the resistive power imposed on the wheels of a vehicle. It consists of a dynamometer that is coupled via gearboxes to drive lines that are directly connected to a set of rollers upon which the vehicle is placed. The rollers can be adjusted to simulate the required driving resistance [15]. As the tests were conducted on chassis dynamometer connected to a single-axle of the vehicle, it is able to simulate the vehicle road load power demand as a function of speed and the inertia of vehicle. During application of a driving cycle, the load is controlled by a pneumatic system that controls axle load with the side lying eddy current brake to the roll, which is used on a wear-measuring system as an information resource for power investigation. A handheld controller was set to monitor and change the water flow based on a variety of control parameters including wheel speed. The test rig is equipped with an automatic overload protection to prevent damage to the tire. Fig. 2 shows the test vehicle on dynamometer and measurement equipments [16].

Fig. 2: Test vehicle and measuring equipments

Portable version of infrared gas analyzer is used during the experimental tests. A HOMANS gas analyzer equipped with gas sampling probe is used to collect the exhaust gas from the muffler. The gas is then filtered and dried before entering the analyzer. Magnetic inductive pickup transducer is used to measure the vehicle speed in km/h. Fig. 3 shows a schematic view of the laboratory chassis dynamometer and the instrumentation system. For emissions test continuously proportioned samples of diluted exhaust mixture and diluted air are collected. A gas analyzer is used to measure diluted exhaust contents of CO, O_2, HC and CO_2.

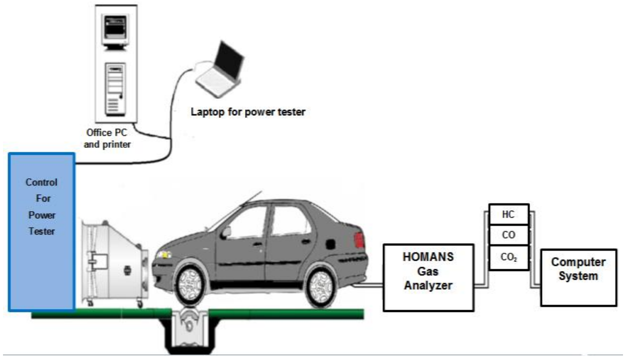

Fig. 3: Schematic of test setup and instrumentation system

4. Results and discussion

4.1. Road performance and acceleration

Figs. 4 to 6 depict responses of measured road power (P) and road torque (M) from vehicle tests at 100 km/h for MT, AT and CVT powertrains respectively. The values of power and torque increases for an increase in the time (acceleration mode) up to 32 s with values of 259 Nm and 21 kW for MT. The corresponding values of 40 s with values of 130 Nm and 12 kW for AT; and 40.5 s with values of 150 Nm and 40.5 kW for CVT. The deceleration mode depicted a decrease in performance values till 75 s for MT, 54 s for AT and 52.5 s for CVT. The road torque exhibited some fluctuations for MT. Figs. 7 to 9 show the measurements of time (T) and distance (S) from which acceleration (A) is calculated for the considered transmissions respectively. For MT, a distance of 145 m can be gained in about 18.34 s, resulting in an acceleration of 5.73 m/s^2 at instantaneous speed of 105 km/h. For AT, a distance of 360 m can be gained in about 22.5 s resulting in an acceleration of 4.49 m/s^2 at instantaneous speed of 101 km/h. For CVT, a distance of 100 m can be gained in about 19.17 s resulting in acceleration of 5.27 m/s^2 at instantaneous speed of 101 km/h.

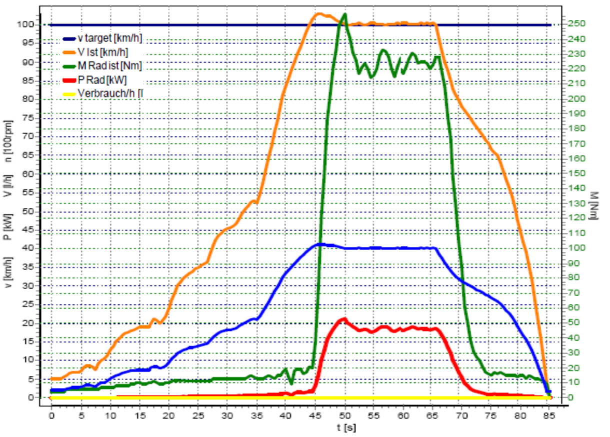

Fig. 4: Vehicle road performance for MT at 100 km/h

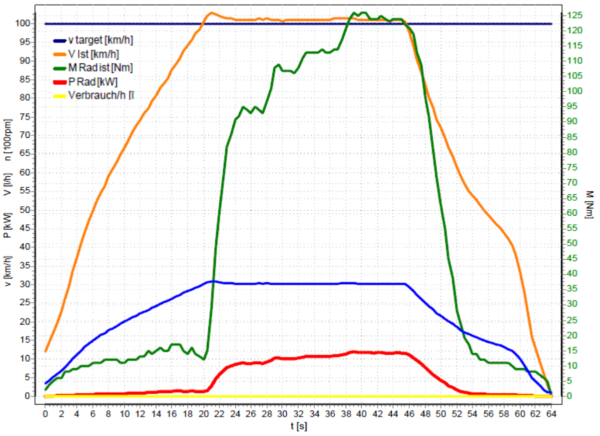

Fig. 5: Vehicle road performance for AT at 100 km/h

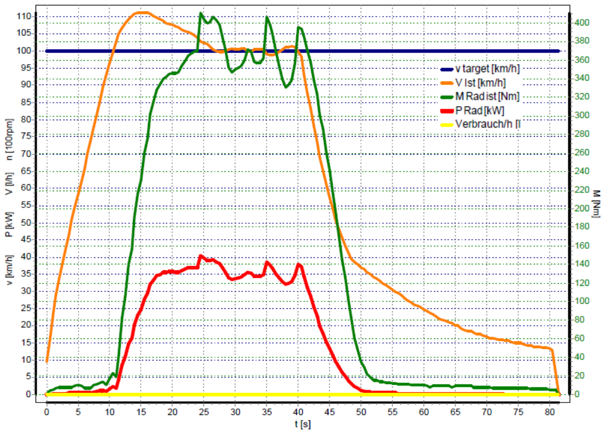

Fig. 6: Vehicle road performance for CVT at 100 km/h

The fluctuations in speed for MT (see Fig. 7) are attributed to the manual gear shifting process. During standard upshift in a vehicle fitted with either AT or CVT there is no torque interruption to the wheels as observed by flat longitudinal acceleration during the shift. In order to establish a comparative assessment of road performance and acceleration at vehicle cruising speeds of 40, 60, 80, 90 and 100 km/h, Figs. 10 to 13 show the individual maximum values of power, torque, acceleration and time respectively. Table 3 gives the maximum values and their corresponding vehicle speeds for all the three powertrain transmissions.

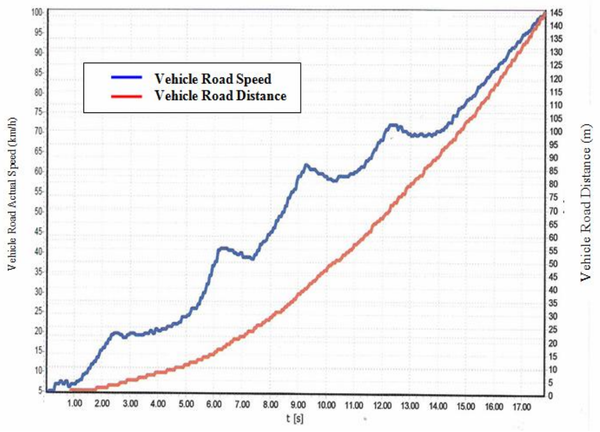

Fig. 7: Vehicle speed and distance for MT

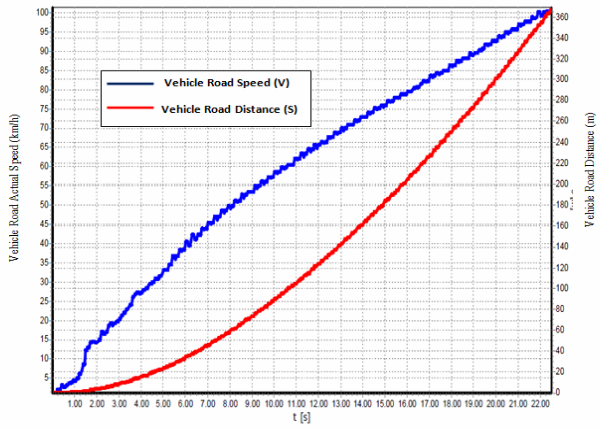

Fig. 8: Vehicle speed and distance for AT

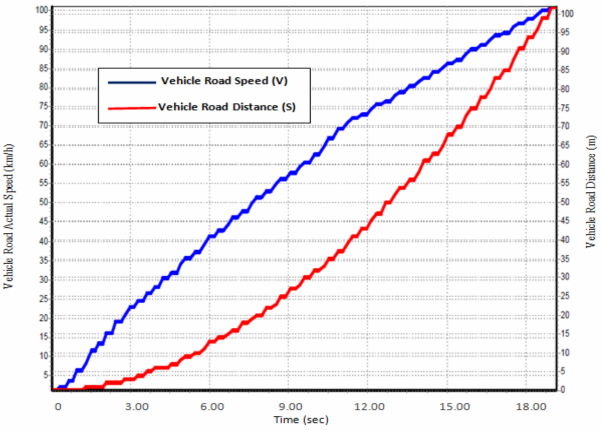

Fig. 9: Vehicle speed and distance for CVT

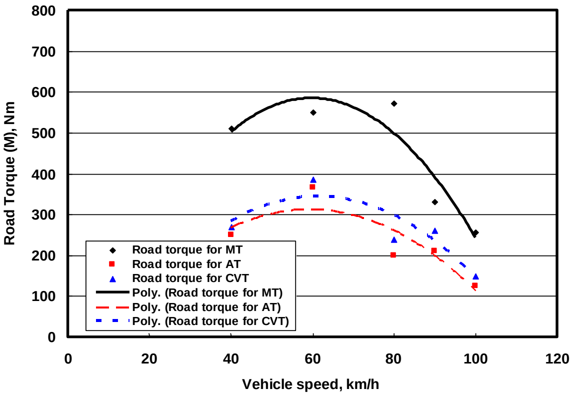

Fig. 10: Max. torque vs. Vehicle speed

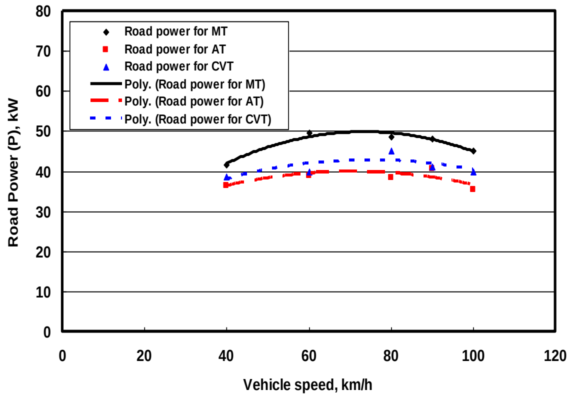

Fig. 11: Max. power vs. Vehicle speed

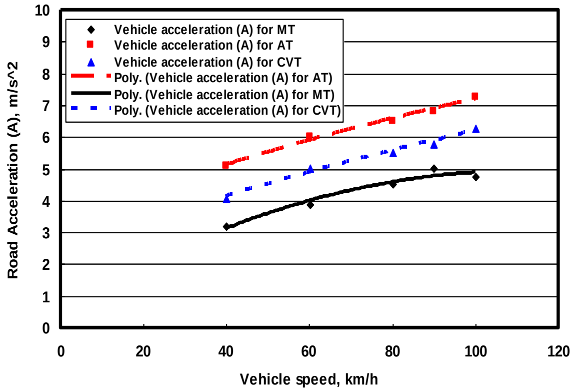

Fig. 12: Max. acceleration vs. Vehicle speed

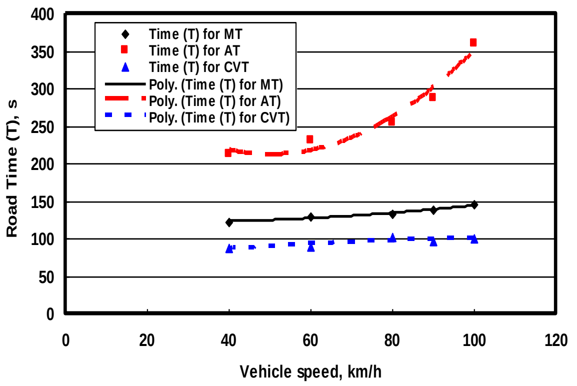

Fig. 13: Max. time vs. Vehicle speed

Table 3: Max. vehicle road acceleration and corresponding speed

Power train	P		M		At 100 km/h	
	Value kW	Speed, km/h	Value, Nm	Speed, km/h	A, m/s^2	T, s
MT	50	70	590	62	4.99	149.5
AT	43	80	310	60	7.05	350
CVT	46	75	350	63	6.10	100

4.2. Engine-out emissions

Based on the ECE-15, the vehicle emissions of CO, CO_2, HC and EI respectively from the gas analyzer measurement at road speed 100 km/h with MT, AT and CVT powertrains are shown in Figs. 14 to 16. The variation of all emission contents except for CO_2 over time is consistent with the driving cycle. Due to scattered data, the responses are grouped into 3 ranges of time duration namely, T1 for 15-25 s, T2 for 50-100 s and T3 for 125-200 s. The CO, HC and EI computed for CVT is the lowest level followed by AT and MT for all three time durations. The CO_2 measured in T1 and T2 time durations for AT is the lowest level followed by CVT and MT. The CO_2 measured in T3 duration for CVT is the lowest level followed by AT and MT. In order to establish a comparative assessment, an average value was created for emission parameters at vehicle cruising speeds of 40, 60, 80, 90 and 100 km/h and presented in Figs. 17 to 20. Table 4 gives the minimum values for the emission parameters and their corresponding vehicle speeds for all the three powertrain transmissions. Furthermore, the vehicle fitted with CVT gave lowest emissions of CO, CO_2, HC and EI in the time period of measurement compared with the other two transmissions considered in this study.

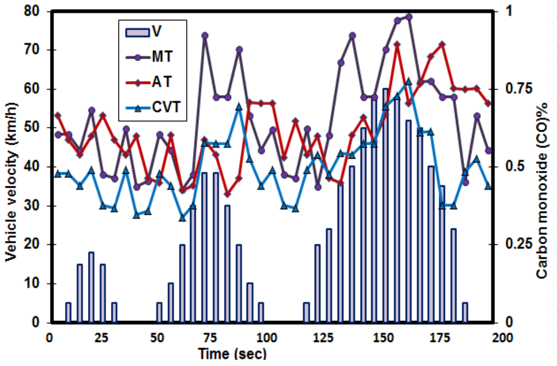

Fig. 14: CO emissions for MT, AT and CVT

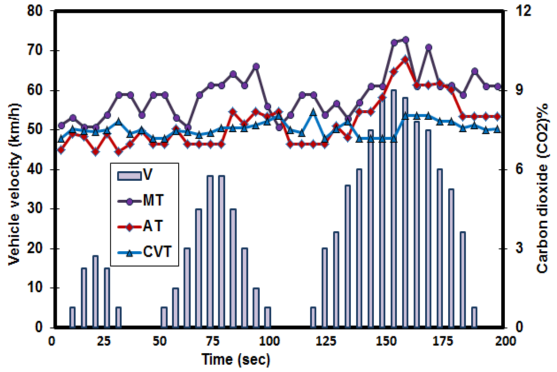

Fig. 14: CO_2 emissions for MT, AT and CVT

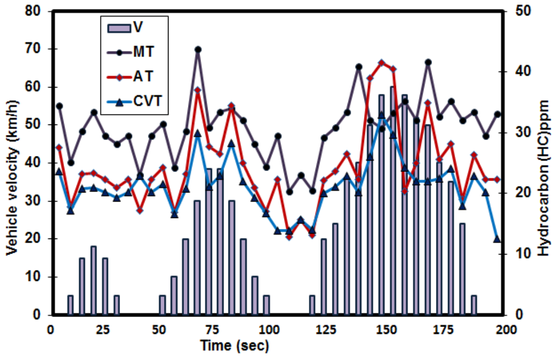

Fig. 15: HC emissions for MT, AT and CVT

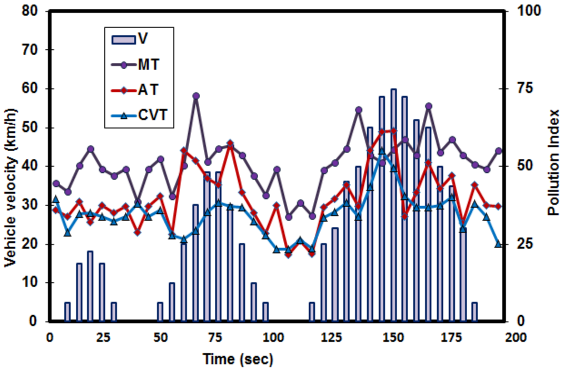

Fig. 16: EI for MT, AT and CVT

Table 4: Minimum values of vehicle emissions

Power train	Min. value of emission (60 km/h)			Min. EI and Speed	
	CO %	CO_2 ppm	HC ppm	Value	km/h
MT	0.64	7.20	24.64	44.50	70
AT	0.61	7.38	23.94	33.65	62
CVT	0.46	7.17	20.37	31.15	60

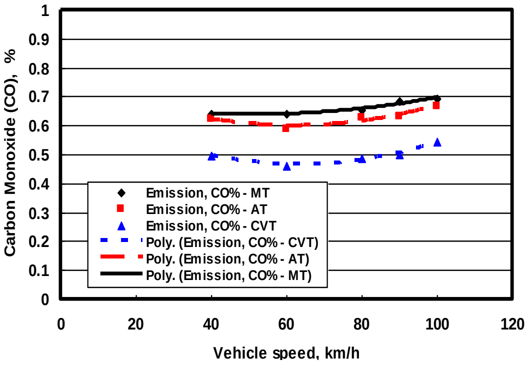

Fig. 17: CO emissions vs. Speed

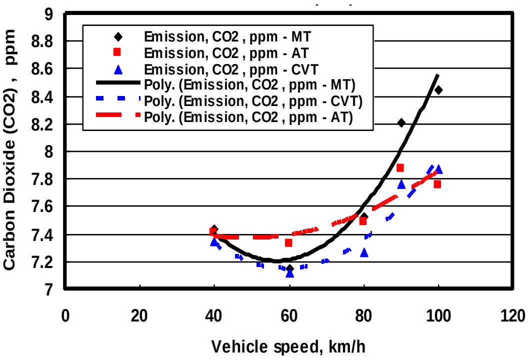

Fig. 18: CO$_2$ emissions vs. Speed

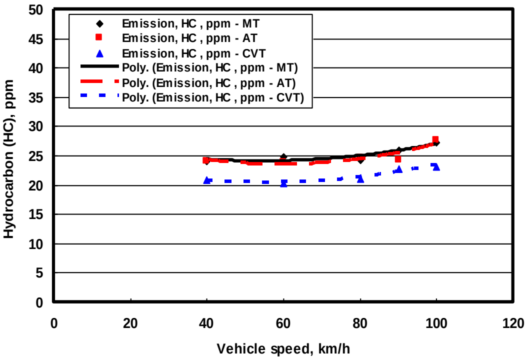

Fig. 19: HC emissions vs. Speed

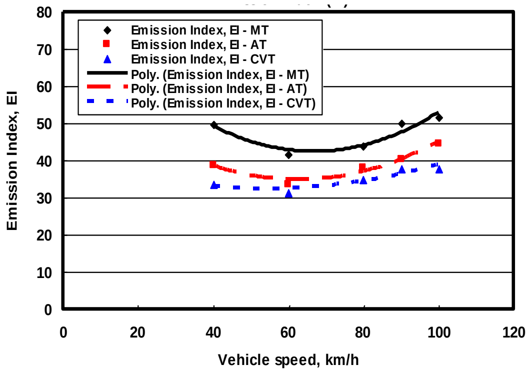

Fig. 20: EI vs. Speed

4.3. FCR

Fig. 21 shows the time history of FCR for all the transmissions considered in this study. The road speed is 100 km/h. The variation of the FCR is consistent with the profile of the driving cycle. This Fig. is plotted for all the powertrain transmissions and vehicle speed with respect of time. It is observed that the data are very picky, therefore it is decided to Similar to previous plots, the FCR responses are divided into T1 to T3 duration ranges of time. The FCR computed for CVT is the lowest rate followed by AT and MT in all the three durations. In order to establish the comparative assessment, an average FCR at vehicle cruising speeds of 40, 60, 80, 90 and 100 km/h is given in Table 5. The vehicle when equipped by the CVT exhibits the lowest FCR in the time period of test compared with the other two transmissions considered in this study.

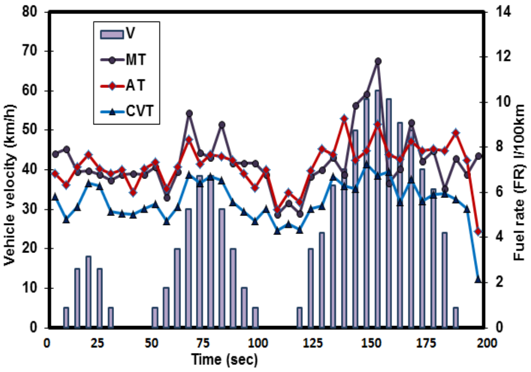

Fig. 21: FCR for MT, AT and CVT

Table 7: Average FCR for MT, AT and CVT, Min. value is in bold

Power train	Average FCR, l/100km				
	40 km/h	60 km/h	80 km/h	90 km/h	100 km/h
MT	7.55	**7.16**	7.22	7.72	7.82
AT	6.91	**6.73**	6.44	7.77	7.52
CVT	5.86	**5.67**	5.48	5.68	6.59

4.4. Powertrain transmissions assessment

The percentage of vehicle power, EI, fuel economy and acceleration performance of various transmissions as compared to MT are presented in Table 9 and Fig. 22. The acceleration performance (A) exhibits high percentage for AT (33.65%) followed by CVT (31.15%) and MT. The MT has provided better FCR than the AT and CVT. This FCR is due to the gear shift schedule.

Table 9: Vehicle performance parameters, EI and fuel rate of AT and CV transmissions as compared to MT

Power train	Performance parameters							
	P, kW	%	A, m/s^2	%	EI	%	FCR l/100 km	%
MT	50	0.0	4.4	0.0	44.50	0.0	7.16	0.0
AT	43	7.69	4.8	1.43	33.65	24	6.73	6.0
CVT	46	15.38	5.1	14.29	31.15	30	5.67	20.8

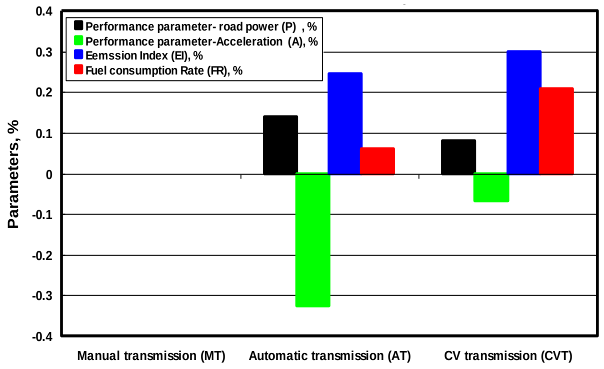

Fig. 26: Vehicle power, acceleration, EI and FCR of AT and CVT compared to MT powertrain

5. Conclusions

The driveability, power, torque, acceleration, exhaust emissions and fuel consumption of the gasoline midsize saloon vehicle drove under ECE-15 driving cycle (part 1) for urban area were assessed using a test vehicle on a standard chassis dynamometer. The test vehicle was equipped with interchangeable Mt, AT and CVT powertrains. From the measured emission components, EI and FCR were calculated. Fluctuations in the torque (M) results were observed for MT, while smooth increase was observed for AT and CVT. This is attributed to the manual gear shift, where a torque interruption to the vehicle wheels occur and the longitudinal acceleration was reduced during the shift. However, during a standard upshift in a vehicle fitted with either AT or CVT there is no torque (T) interruption to the wheels. The assessment of emissions data indicate indicated that their variation is consistent with the driving cycle profile for all emission contents other than CO_2. The vehicle when equipped by MT gave higher vehicle emissions of CO, CO_2 and HC in the measurement time period when compared with the other two transmissions considered in this study. Both AT and CVT have lesser FCR than MT in speed range up to 100 km/h. High speed ratio of AT and CVT allows to optimize the engine's thermal efficiency and to reduce the FCR in spite of its lower efficiency. On the other hand, the absence of friction clutch makes the AT and CVT more comfortable with respect to MT and allows the running of vehicle at very low speed without any problem arising from the engage/disengage of clutch.

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