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Fuel economy improvement based on a many-gear shifting strategy

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Abstract
Considering the engine operating condition in terms of engine load and engine speed, a fuzzy decision making system has been developed. The objective was to controlling the engine operating point in the engine torque-rpm map, in order to enhance fuel economy. The main idea stems from the approach of tracking the defined target curve in the engine map similar to the CVT control criteria. To provide resemblance between a traditional geared transmission and a CVT, a many-gear transmission concept was introduced. A Fuzzy control was utilized by defining proper membership functions for the inputs and output. The efficient fuel consumption curve in the engine map was taken as the target of controller. The effect of engine output power on fuel consumption has also been taken into consideration. Making use of ADVISOR software, vehicle simulations was performed for the many-gear base case and a very good consistency was found with the CVT case. As a result the fuel consumption was found to become considerably less than existing values. The developed strategy was then applied to other cases including conventional manual and automatic transmissions and improvements in the fuel economy was observed.

Keywords: Gear shifting strategy; Fuzzy control; Fuel economy; AMT; AT.

1. Introduction
Passenger comfort and fuel efficiency have always been two important subjects in automotive design industry. Although the driving of a car equipped with a manual transmission may be pleasant on highways, the situation is completely opposite inside large cities due to heavy traffic. Automatic gear shifting systems including conventional Automatic Transmissions (AT), Automated Manual Transmissions (AMT) and Continuously Variable Transmissions (CVT) are proper solutions to tackle this problem. Moreover, strict regulations on emission reduction in one hand and fuel economy on the other hand are additional driving forces towards new solutions.
An important subject in automatic transmission design is gear shifting schedule which determines shifting times according to a predefined strategy. Among the various kinds of strategies investigated by designers and researchers in many years, only a limited number of publications is available to the public.
Xiafeng et al [1] have established the dynamic torque and fuel consumption models of engine, described by a multilayer feed-forward neural network. They have calculated the optimal dynamic and economical shift schedules with a 3-parameter model. The automatic shift schedule has taken the influence of acceleration of vehicle into consideration and improved the vehicle fuel economy compared with conventional 2-parameter schedules up to 1.8%.

Nelles [2] has proposed a new driving strategy called IntelligenTip, which is capable of learning from driver's style of driving via +/- buttons whenever the automatically selected gear seems inappropriate. The core of this method is the fuzzy systems whose membership functions are adapted. This approach offers a number of advantages such as the stable and fast convergence to the unique optimum. It is demonstrated that the strategy yields an individualization of the shift behaviour and is robust with respect to different driver types.

Hayashi et al [3] have designed an optimal transmission controller using a Neuro-Fuzzy approach for an automobile with variable loads. The vehicle loads and driver's intention are estimated from the signals of the status sensors by fuzzy logic. Then a neural network is fed by these data and an experienced driver teaches it to act in an optimal gear shifting manner such that a vehicle operator feels comfortable even during automobile load changes.

A tabular approach was proposed by Qin et al [4] for cruise control gear selection based on offline calculations. A table is chosen at the time of decision making according to the driving condition. Each table contained shifting boarders in vehicle load-speed map obtained from empirical experiments. Yang et al [5] have investigated driver’s actions on accelerator and brake pedals and tried to categorize these actions for gear shifting purposes.

Using engine state and driver's intention, Mashadi et al [6] have discussed a gear shifting strategy with the application of fuzzy control method using a two-layer controller. In the first layer two fuzzy inference modules were used to determine necessary outputs and in the second one the decision of shifting was made by upshift, downshift or maintain commands. The behaviour of fuzzy controller was examined by making use of ADVISOR software. The dependency of fuel economy to the driving cycles and in turn the influence of traffic conditions is also taken into consideration by Montazeri and Asadi [7].

In the current work, a gear shifting strategy with emphasis on fuel economy has been developed and Fuzzy decision making rules have been utilised. This approach is derived from the very concept that only a CVT can follow the desired working points on the engine Torque-RPM map. In order to make this approach applicable to conventional transmissions, a many-gear transmission concept has been established.

2. Fuel economy and gear shifting effects

Many approaches are known as feasible to improve fuel economy of a ground vehicle; including optimization of intake & fuel injection systems, increasing volumetric efficiency, optimising combustion chamber, etc. With the application of these methods, the structure and performance of the engine will directly be affected and fuel consumption map will be so amended that more areas of Torque-RPM map is assigned to fuel efficient points. By means of these concepts, one can expect reductions of fuel consumption up to 10% [8].

In addition to these techniques which obviously influence the function of the engine itself, it would also be possible to optimize the manner in which the engine is utilized during driving. Improvement of power train system is a method of optimizing the engine operating regimes. Possible modifications of power train systems can be divided into hardware and software categories. The hardware modifications affect the structure and mechanism of the power train system and involve selection of different transmission types and gear ratio design. These types of conceptual and structural modifications of power train system are believed to improve the fuel economy by 3 to 8% [8]. Software modifications, on the other hand are only applicable in Automatic Transmissions (AT), Automated Manual Transmissions (AMT) and Continuously Variable Transmissions (CVT), where making decision on gear shifting and proper position of Engine Operating Point (EOP) is performed by a control unit. Considering diverse factors selected by system designer (e.g. engine speed, engine load, vehicle speed, throttle angle, accelerator pedal angle and brake pedal angle, etc) and according to the shifting strategy, control unit determines the suitable shift action which can be upshift, downshift or no shift. The shifting decision can directly affect the EOP and therefore is a practical way to control the engine state using the software adjustment. Engine state or EOP is not only related to transmission ratio but also several other factors like road condition and driving habit. The software modifications such as geared transmissions' shifting plan can improve the fuel economy by 0.5 up to 2% [8].

3. Vehicle simulation

In order to simulate the performance and fuel consumption of the vehicle, ADVISOR software has been utilized in this work. This program uses backward, semi-static approach and is able to simulate the vehicle motion in defined driving cycles. Conventional shifting map of transmission in the software, which defines the points of shifting according to engine torque and speed in form of diagonals is adopted as basic form for both Automatic and Automated Manual transmissions. Each diagonal defines the shift action point from existing gear number to the previous or next one. Usually, the conventional shifting maps are based on vehicle performance rather than fuel economy; although some modifications are possible to combine performance oriented and fuel economy oriented shifting maps [1, 2]. In manual transmissions, decision of shifting is made by driver, who applies her/his experience to determine the point of shifting, thereby it is hard to expect fuel efficient shifting plan.

3.1 Manual 5-step transmission

As a reference, a vehicle with specified characteristics and a 5-step Manual Transmission has been simulated while tripping NEDC driving cycle using ADVISOR default shift map By means of this simulation, the placement of EOPs has been recorded in Torque-RPM map and also the nominal engine fuel consumption has been calculated. Comparing the placement of EOPs with the specific fuel consumption contour, as shown in Figure 1, one can simply observe how the operating points are scattered during vehicle motion. EOPs are extended in direction of RPM axis as a result of gear shifting (caused by sudden change of engine speed) and the smooth acceleration of vehicle in an engaged gear. The same diversity exists in the direction of torque axis which is caused by engine load changes during the trip. The variation of engine load is normally imposed by driver and road conditions. In the area of negative torques, a concentration of operating points which are resulted in various engine speeds can clearly be seen. This could be recognized as a result of engine operation during vehicle deceleration with closed throttle. In such condition, braking effect of engine will be appeared because of opposite direction of power flow. Although the engine load is very small in this state, fuel consumption is not desired due to poor engine specific fuel consumption.

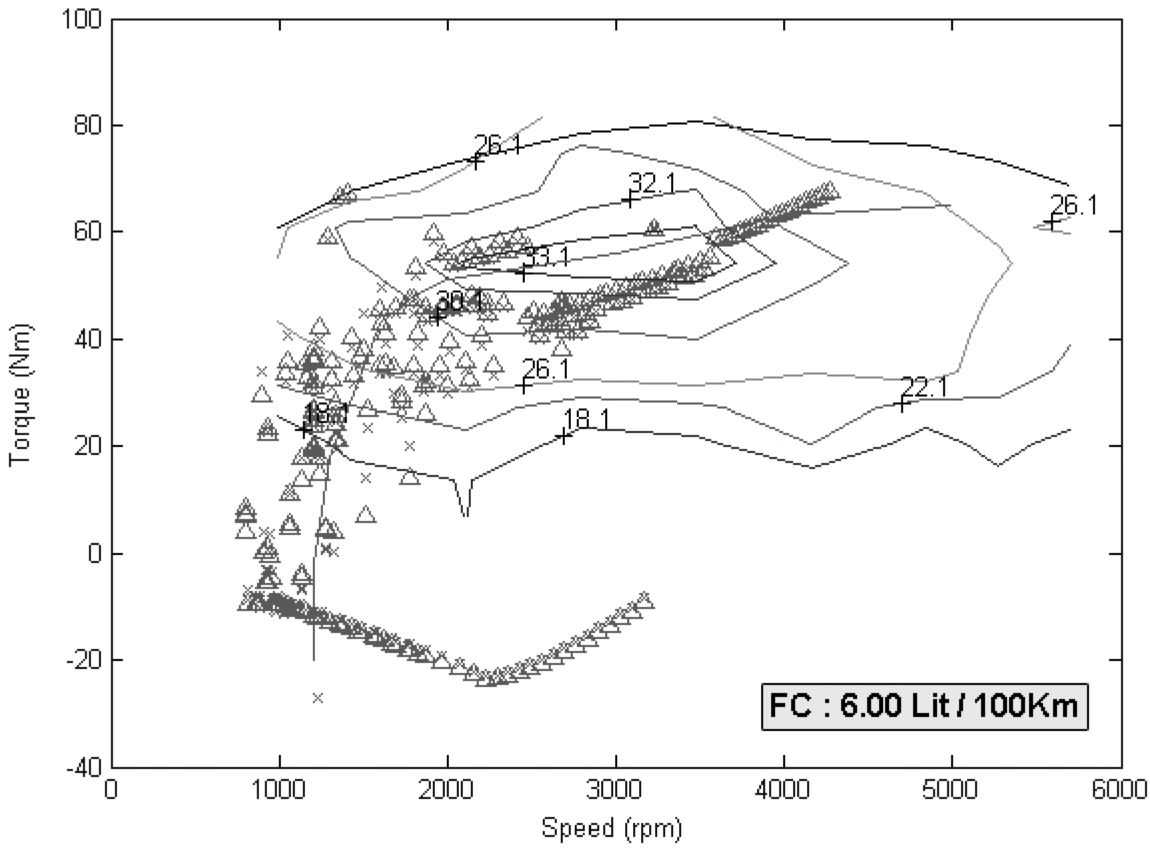

Figure 1. EOP placement of ADVISOR default shifting map for MT

3.2 Manual 5-step transmission

In another approach [6], default shifting map of ADVISOR has been replaced by a set of fuzzy decision making rules. Driver's intention is the major factor in setting the fuzzy rules of this strategy. It should be noted, that fuel consumption of vehicle has not been taken into consideration. Figure 2. shows the range of EOPs resulted from running the same vehicle and gearbox in NEDC driving cycle using modified strategy.

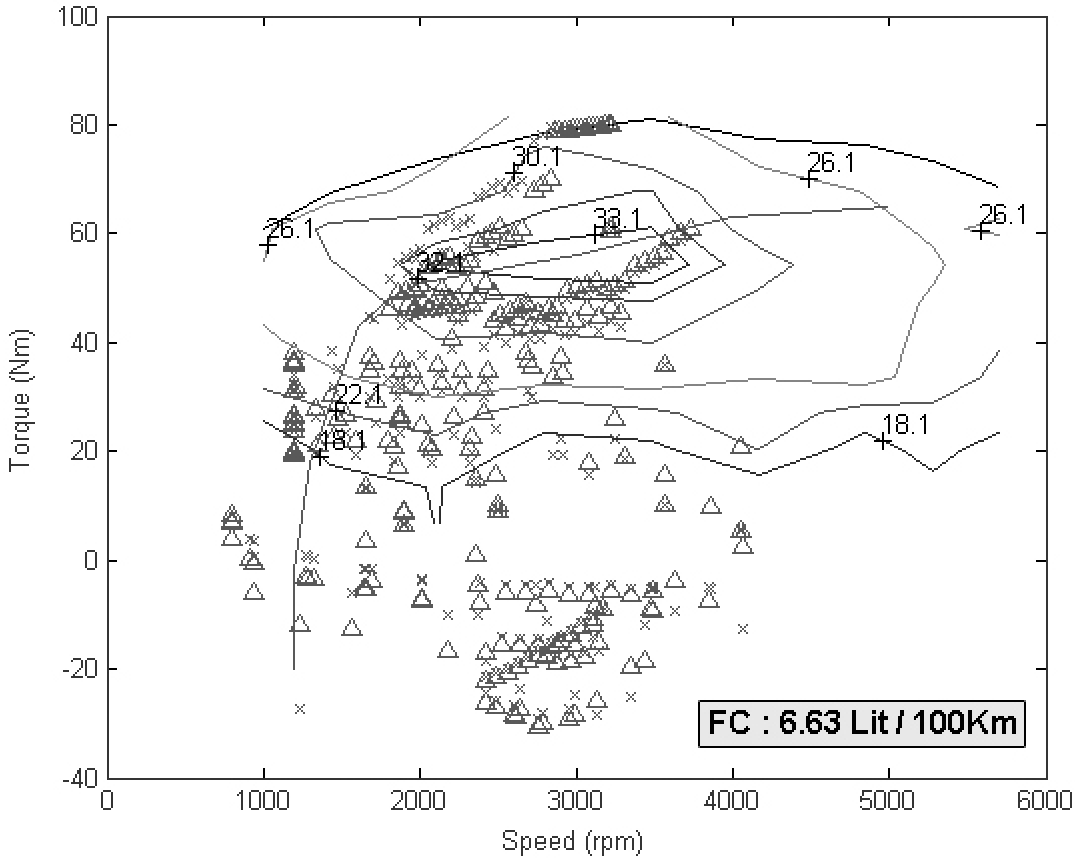

Figure 2. EOP placement of driver’s intention shifting strategy [6] for MT

Comparing the results of the two simulations reveals differences in the scatterings of operating points in engine Torque-RMP map for the two cases. Operating points are mostly extended in high engine speed ranges and small number of points is located near to fuel efficient area of the map. Running the engine in full load condition, which happens during this simulation, completely deteriorates the fuel economy due to high engine torque and speed. Poor fuel economy of this method could be predictable because the developed fuzzy controller was intended to reflect the driver's needs by processing the incoming signals from accelerator and brake pedals; consequently fuel consumption of the vehicle was not concerned.

3.3 Conventional 4-step automatic transmission

Besides limit losses in gears and bearings, an inevitable loss will occur in this case because of poor hydraulic performance of torque converter. The imposed loss leads to decrease of transmission overall efficiency and fuel economy. Shifting map of these transmissions in ADVISOR has been defined as diagonals in Torque-RPM map of engine which is a common method; however these diagonals could be considered in Throttle-Vehicle speed map too. In order to compare the fuel consumption of the same vehicle, equipped with a conventional Automatic Transmission, an adapted simulation has been performed. Figure 3. shows the placement of EOPs of the vehicle running in NEDC driving cycle. The EOPs are clearly more spread in various engine speeds compared with those of 5-step manual transmission. The reason for this difference can be justified owing to less gear steps and in turn increase of gear ratios between following gears and eventually uncontrollable jumps of EOP during gear shiftings. These jumps can result in poor fuel efficiencies of the vehicle as illustrated.

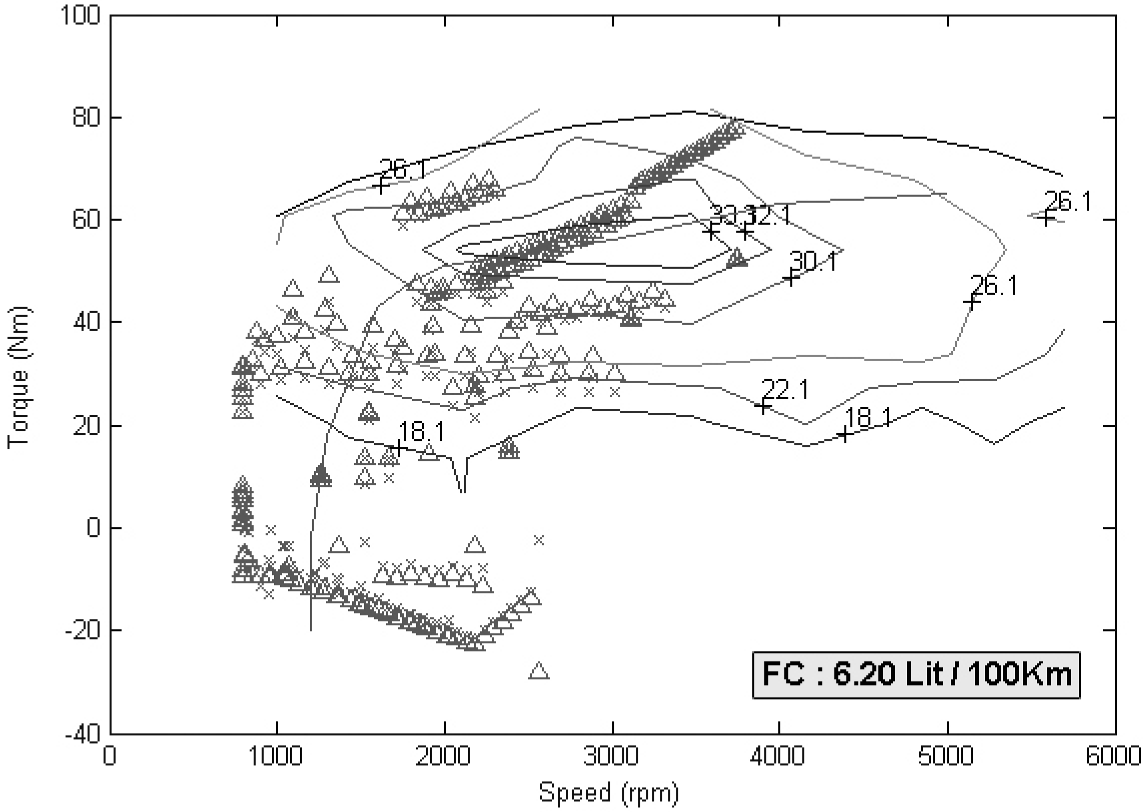

Figure 3. EOP placement of ADVISOR default shifting map for AT

4. Shifting strategy based on fuel economy

In order to apply an interface for making gear shifting decision, the default algorithm of ADVISOR was replaced by a Fuzzy module which uses MIN/MAX or Mamdani inference method. Figure 4 shows the schematic of reformed transmission control box of software after applying a Fuzzy interface module. Upshift, downshift or noshift decisions are made according to input values and governing rules.

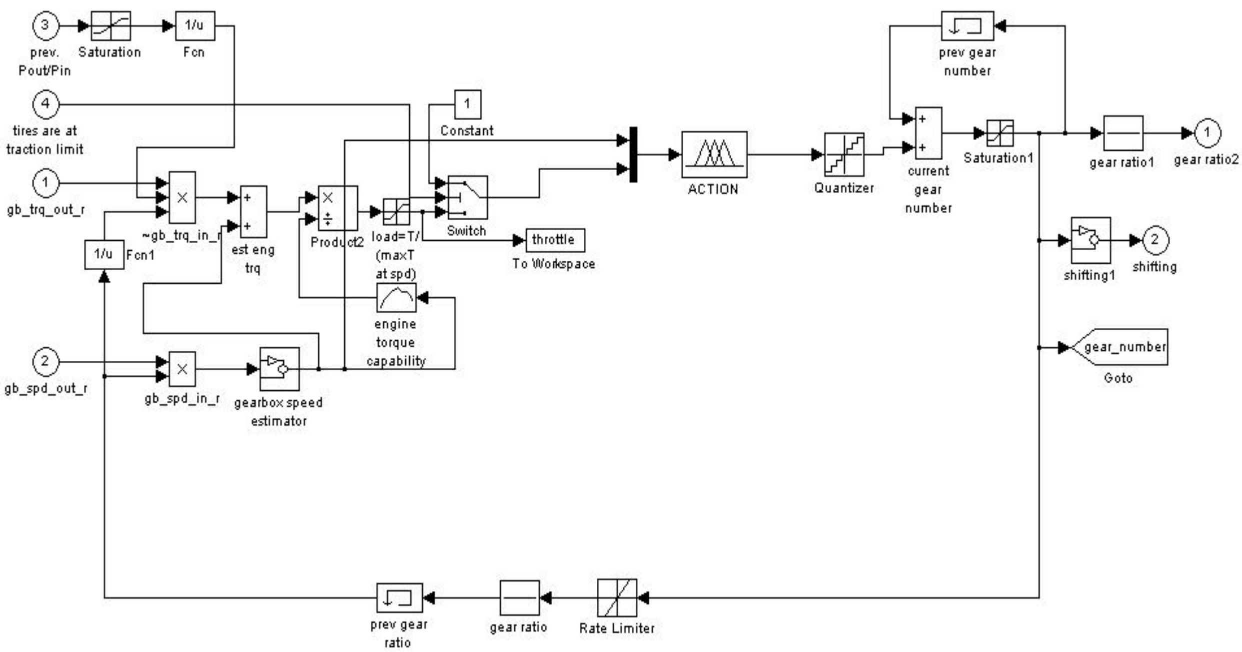

Figure 4. Reformed transmission control box of ADVISOR

4.1 Inputs and outputs of fuzzy controller

The aim of Fuzzy inference system is to control the operating point of engine so that control on fuel consumption could be achieved. Engine speed and load are two main parameters that locate the working point of engine in all related maps, consequently these have been considered as controller inputs. The inputs should be Fuzzified in linguistic terms using Fuzzy membership functions before they can be utilised in Fuzzy controller. Engine speed demonstrates the position of EOP in the X axis direction of Torque-RPM map. The membership function of engine speed in a range 50-500 rad/sec is described in Figure 5 in terms of triangular functions in linguistic terms: very low, low, medium, high and very high.

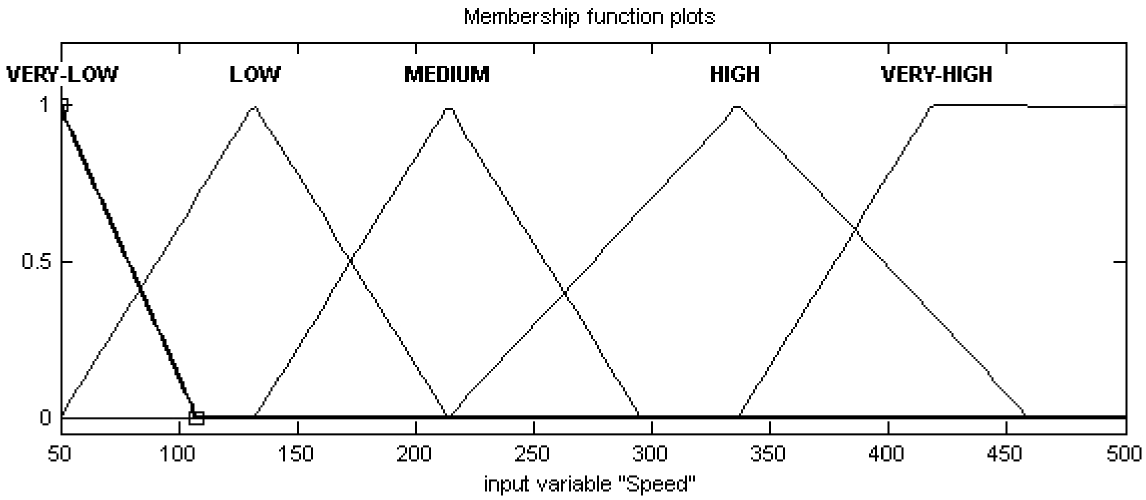

Figure 5. The membership function of engine speed

Engine load is considered as second input of Fuzzy controller and indirectly affects the position of EOP in Y-direction of torque-RPM map. Generally, engine load is defined as engine current torque divided by maximum torque at the same engine speed (equation 1). In ICE literature it is also estimated according to the throttle value. The higher throttle results in more loads on the engine and more torque necessary to overcome the load [9]. In mathematical terms,

$$Load = \frac{T_e}{T_{\max} @ rpm} \cong \alpha_{throttle} \tag{1}$$

The engine throttle ratio in the range of 0-1 is described in Figure 6. Zero and 1 values mean idle and full load operating conditions of engine respectively. The intermediate values are evaluated in terms of triangular functions in linguistic terms: low, medium and high. By means of these definitions, all possible positions of the EOP are covered and the map of Torque-RPM is completely meshed by overlapped fuzzy membership functions. The fuzzification of output space is made in terms of membership functions shown in Figure 7 The output membership functions are described in linguistic terms by defining -1, 0 and +1 as decisions to Downshift, Noshift and Upshift,. Using this system, the gear shifting decision can be made by the controller with mapping the input space to the output space and application of Fuzzy rules.

4.2 Basic controller concepts

The development of Fuzzy rules, in general, is based on operator's experiences or prediction of desired state parameters. The engine operating points and fuel consumption that are necessary parameters for the rule developments are imperceptible for the driver and such helping experience does not exist. The development of fuzzy statements which would control the engine fuel consumption, therefore, should be carried out using desired state prediction of engine. Finding reasonable areas of EOPs on Torque-RPM map is the most useful concept in development of Fuzzy rules. Theoretically, spark-ignition ICE shows a better fuel consumption characteristic in lower engine speeds and higher loads comparing with higher speeds and lower loads [10]. Generally, performance based strategies intend to shift the gears in high engine speeds, so that the maximum traction and acceleration can be utilized. This concept leads to vehicle acceleration in low gears and operation of the engine in higher speeds and lower loads. This operating condition of engine lies on poor fuel efficient areas of engine map.

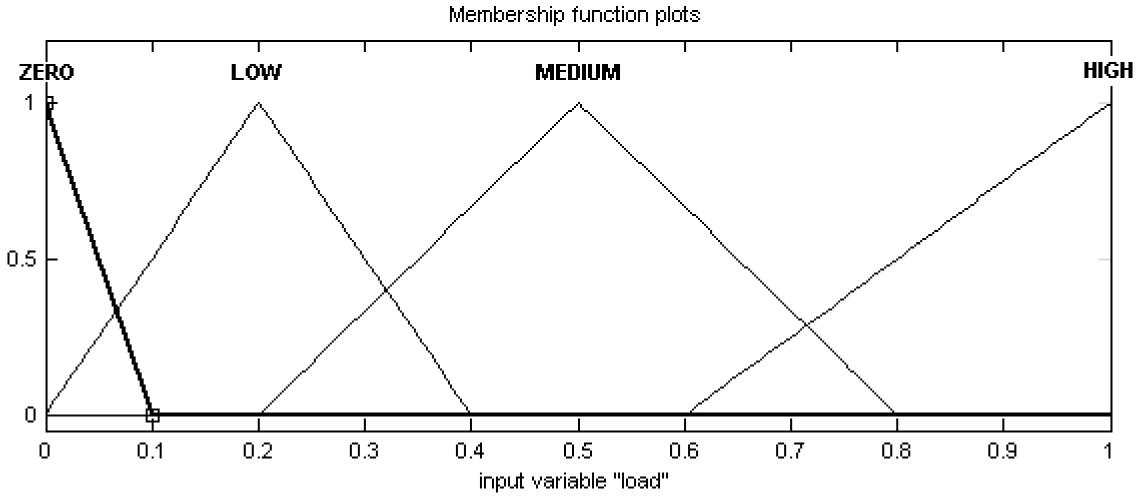

Figure 6. Membership functions of engine load

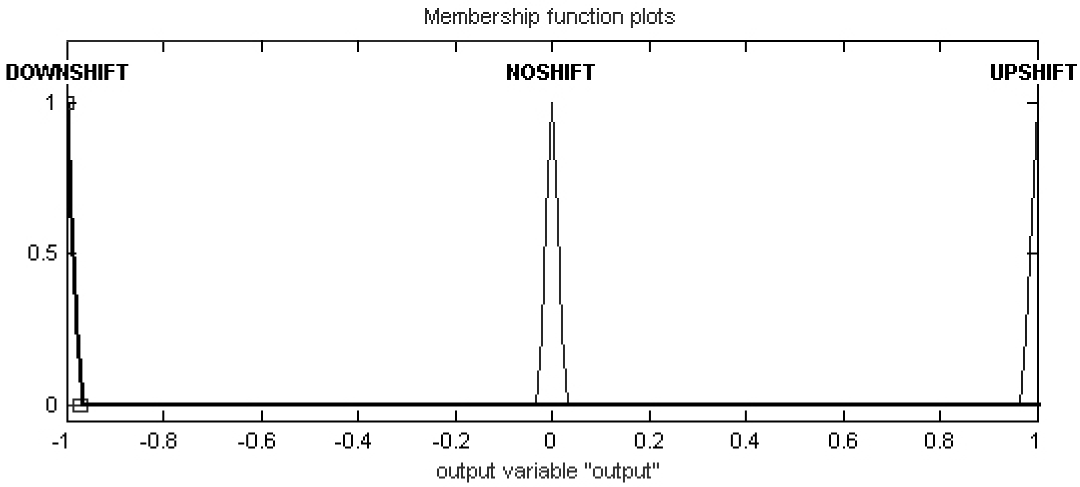

Figure 7. Membership functions of output

One idea would be approaching the EOPs to the range of fuel efficient area by applying appropriate Fuzzy rules. The simulation result of this attempt for the NEDC driving cycle is shown in Figure 8. The density of EOPs can be clearly distinguished in the speed range of fuel efficient area. The shift action is performed by required upshift and downshifts, so that the operating point of engine is always kept within the mentioned speed range; nevertheless the fuel consumption does not show any improvements compared with default strategy of ADVISOR. The result was expected since the engine load was not taken into consideration.

In a second attempt, with consideration of load difference after downshift and upshift, a reformed strategy is adopted whose aim is to approach the EOP to the fuel efficient area with respect to both parameters. Using this method, the operating point is always expected to be close to the fuel efficient area in intermediate speeds and high loads. Downshift action in low speed areas leads to improve the location of EOP however in high speed areas an upshift command can change the EOP to lower speeds and higher torques which is theoretically desired. Results for this approach with the same vehicle data in terms of the placement of EOPs is shown in Figure 9. The distribution of EOPs clearly approaches the desired area this time, but engine fuel consumption is not still as low as expected.

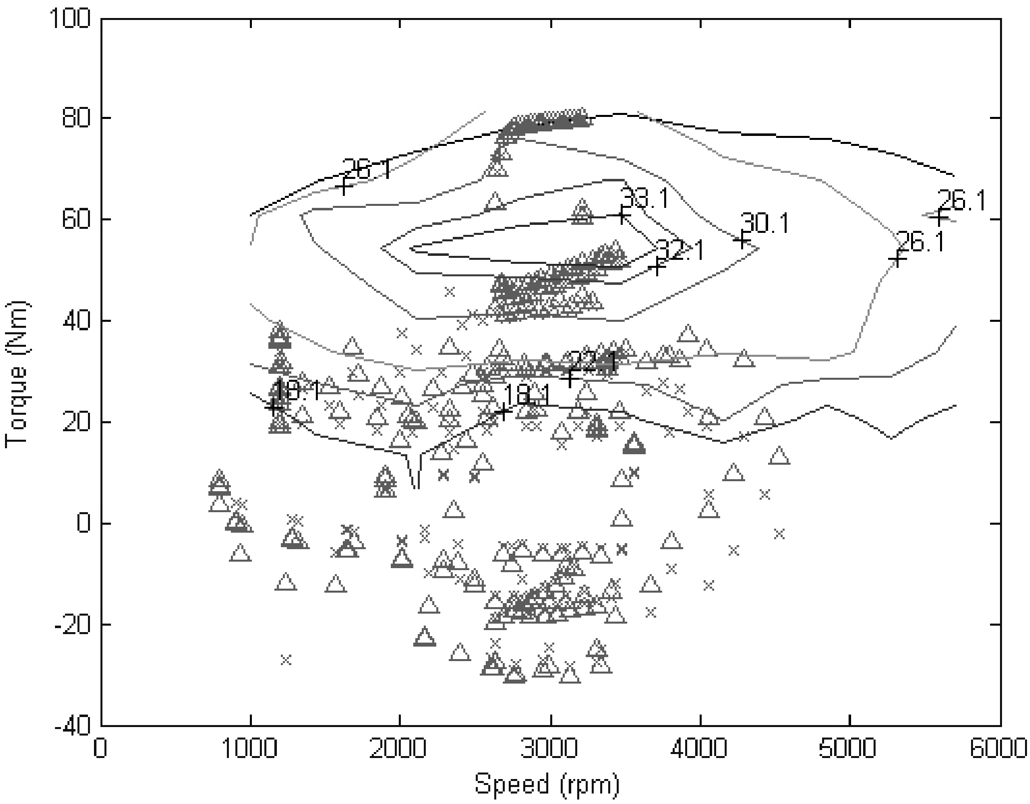

Figure 8. EOP map of 1st attempt(speed)

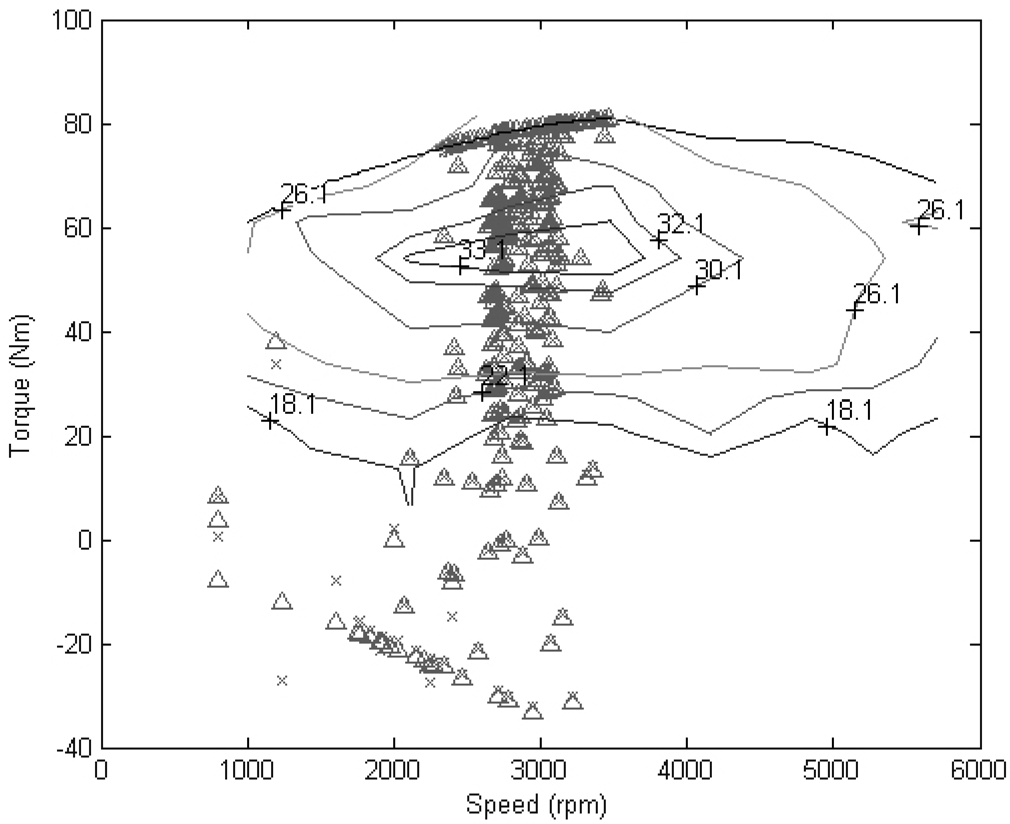

Figure 9. EOP map of 2nd attempt(speed & load)

This result shows that the overall fuel consumption is not related only to engine Specific Fuel Consumption (SFC) and other affecting factors must be involved. This can be investigated by looking at the basic definition of SFC:

$$SFC\ (T,\omega) = \frac{FC}{P} \tag{2}$$

$$P = T \times \omega \tag{3}$$

$$FC = SFC(T,\omega) \times T \times \omega \tag{4}$$

Fuel Consumption (FC), the controlled parameter in this approach, depends not only on the SFC but also on engine speed and torque. Therefore by approaching the EOPs to the SFC efficient zone, the values of engine speed and engine torque are not as proper as necessary. The strategy which pushes the EOPs to this zone cannot guaranty the fuel economy, because all the reduction in fuel consumption which is achieved by running in low SFCs, might be lost by high torques and speeds and lead to invariant or increased fuel consumption. Investigating the results of both approaches demonstrates that a proper strategy should be able to hold a balance between the SFC and engine output power at the same time.

4.3 Efficient fuel consumption curve

The Efficient Fuel Consumption Curve (EFCC) is plotted in engine Torque-RPM map and illustrates the minimum possible SFC in any permanent output power of engine. Tracking EFCC in all necessary engine output powers leads to minimum reachable fuel consumption of the vehicle. In other words, if all EOPs could be located on EFCC during a defined trip, all necessary output powers have been utilised but with minimum SFC. Tracking EFCC of an engine is only possible by a special gearbox which can provide infinite gear ratios, so that change of overall transmission ratio does not lead to sudden change of engine speed and torque which can cause uncontrolled EOP position. Hence a Continuously Variable Transmission (CVT) is the only possible mean to track the EFCC with minimum error. Apart from this advantage, CVTs are facing with some technological difficulties due to their structure including low efficiency which strongly opposes the overall vehicle fuel economy.

4.4 Many-gear virtual transmission

In the present study the idea is to develop an applicable strategy for geared transmissions which resembles the CVT concept to some extent. Obviously, following EFCC like a CVT is an impossible task for transmissions with finite gear ratios. So that a Many-Gear Transmission concept was introduced in order to make the analysis feasible. Increasing the number of intermediate gears provides less difference between two following ratios and in turn less amount of EOP jump during the shift.

In spite of the fact that utilizing more intermediate ratios can help the system to track EFCC more accurately, Fuzzified engine map and membership functions should be fundamentally reconstructed to make it compatible with too many gear ratios. Regardless of technological barriers, too many gear ratios needs squeezing the fuzzy meshes and increasing the membership functions to facilitate all necessary shift actions. Using this method makes the EOP to smoothly move to a neighbouring fuzzy cell after each shift, however, large number of fuzzy rules can dramatically deteriorate the performance of fuzzy controller. Moreover, the existence of many shift actions causes large amount of shift delays and torque losses which are both against the fuel economy. Hence, the increase of intermediate gear numbers should not exceed a certain amount. In order to find out how many gears is too many, a number of investigations were carried out and it was resulted that a transmission with 16 gear steps could be considered a many-gear transmission. The ratios are calculated using geometrical method between the lowest and highest gear ratios.

The extent to which such strategy can be applicable to a typical automobile transmission will also be addressed in the following sections. With reference to the above explained strategy, fuzzy rules of controller are defined and inferred surface is shown in Figure 10.

5. Simulation results

The objective is firstly to investigate how the introduced fuzzy controller will succeed in reducing the engine fuel consumption in a virtual many-gear transmission and secondly whether the same controller could work effectively for conventional transmissions. The simulation is performed using ADVISOR software with modified transmission control box. Three types of gearboxes namely: virtual many-gear, 5-speed automated manual and conventional 4-speed automatic transmissions are considered in order to compare the performance of developed gear shifting strategy. The New European Driving Cycle (NEDC) is chosen for all cases.

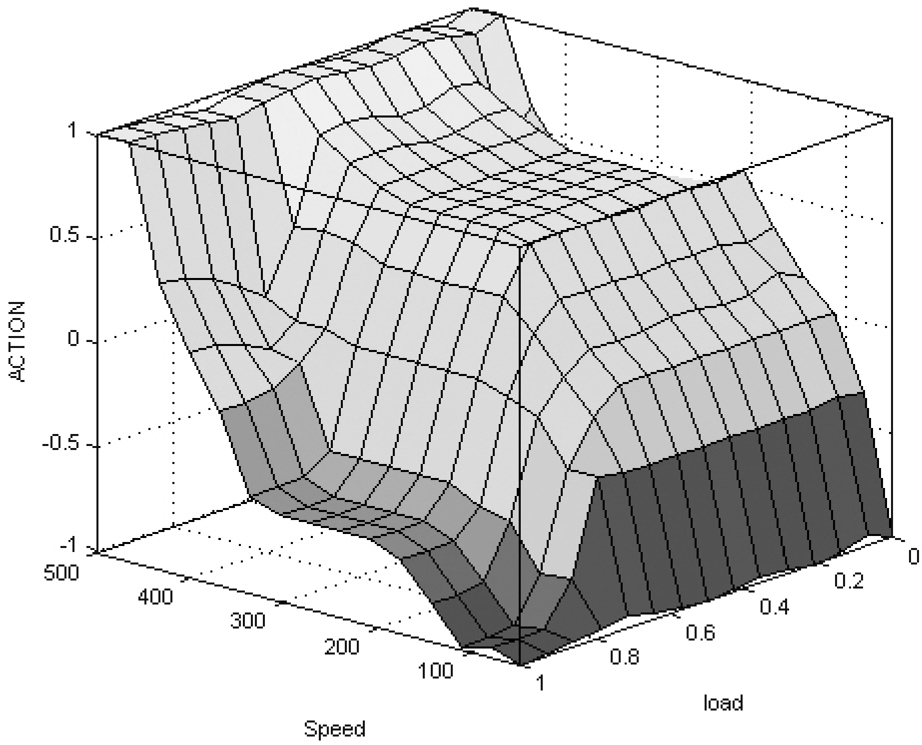

Figure 10. Inferred surface of fuzzy rules

5.1 Virtual many-gear transmission

For the many-gear case with 16 gear ratios, simulation results including engine fuel consumption and the trace of EOPs are recorded in engine Torque-RPM map of Figure 11. EFCC is also plotted in the same figure to make comparison with density of EOPs possible. The investigation of the EOPs trace shows that the application of applied Fuzzy rules has clearly made the points come close to the EFCC. As the gear ratios of virtual transmission are not as many as a CVT, EOP jumps are inevitable; nevertheless they have placed in such a way that the EFCC curve can be regarded as mean value of the points.

5.2 Conventional transmissions

Without making any changes to the controller that was shown to work well for the case of a many-gear transmission, the idea is to see how the same controller will work in the cases of conventional manual and automatic transmissions.

5-speed manual

Shown in Figure 12 is the simulation result for the case of a conventional 5-speed manual transmission. Expectedly, EOPs have been scattered in comparison with many-gear case because of larger ratio differences between two successive gears. Nevertheless, the EOPs have been scattered around EFCC curve. Such performance has clearly reduced the fuel consumption of engine to a considerable extent.

4-speed Automatic

The developed strategy is also applied to a 4-speed conventional automatic transmission. The engine and other subsystems are identical to previous simulation. The simulation results are shown in Figure 13. As the gear numbers are even fewer, the EOPs have further scattered. Although differences between two successive gear ratios have caused larger jumps, nonetheless EOPs are still located near the EFCC curve. This in turn has caused the engine fuel consumption to reduce.

6. Discussion

In order to compare the results of simulations with various shifting strategies, all for NEDC driving cycle, the overall fuel consumption values are illustrated in Table 1.

Increasing gear numbers to 16 and utilization of new shifting strategy with vision of fuel economy (4th row), has caused the overall engine fuel consumption to decrease by 3% compared with the base case (1st row). This was due to the fact that EOPs came closer to EFCC curve while keeping engine output power range at lower values. Application of this shifting strategy to a conventional 5-step transmission (5th row) although shows an increase in the fuel consumption compared with the many-gear case, nevertheless it has improved fuel economy when compared with other shifting strategies such as the base case by 1.6%. When applied to a conventional automatic, the introduced strategy causes about 4.3% less fuel consumption compared with conventional shifting maps.

Reduction of fuel consumption when compared to strategies with no attention to fuel economy e.g. Driver’s intention (3rd row) shows large improvements of more than 10%. Obviously such strategies are based on driver's intention and as a consequence the fuel efficiency of the system impairs dramatically.

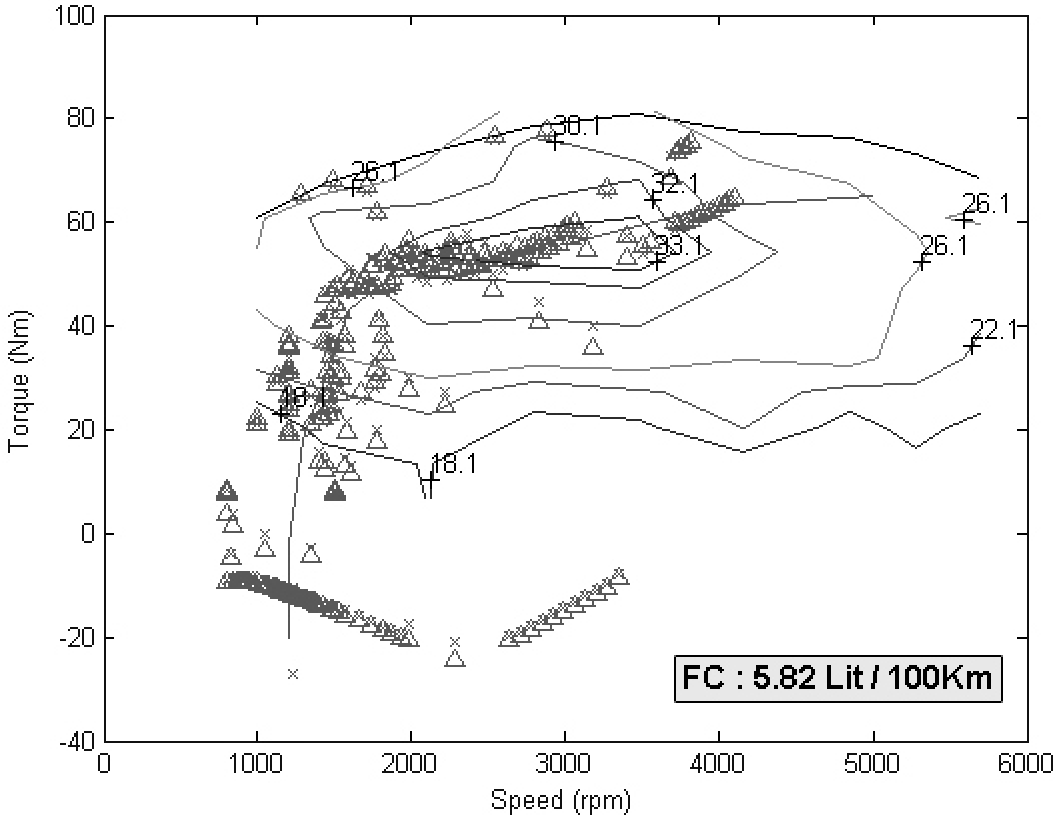

Figure 11. EOP placement of new strategy (16-gear MT)

Table 1. Fuel consumption values

	Type of shifting strategy	Fuel Consumption (lit/100km)
1	ADVISOR – MT (5 G.)	6
2	ADVISOR – AT (4 G.)	6.2
3	Driver’s intention – MT (5 G.)	6.63
4	New Strategy – MT (16 G.)	5.82
5	New Strategy – MT (5 G.)	5.92
6	New Strategy – AT (4 G.)	5.95

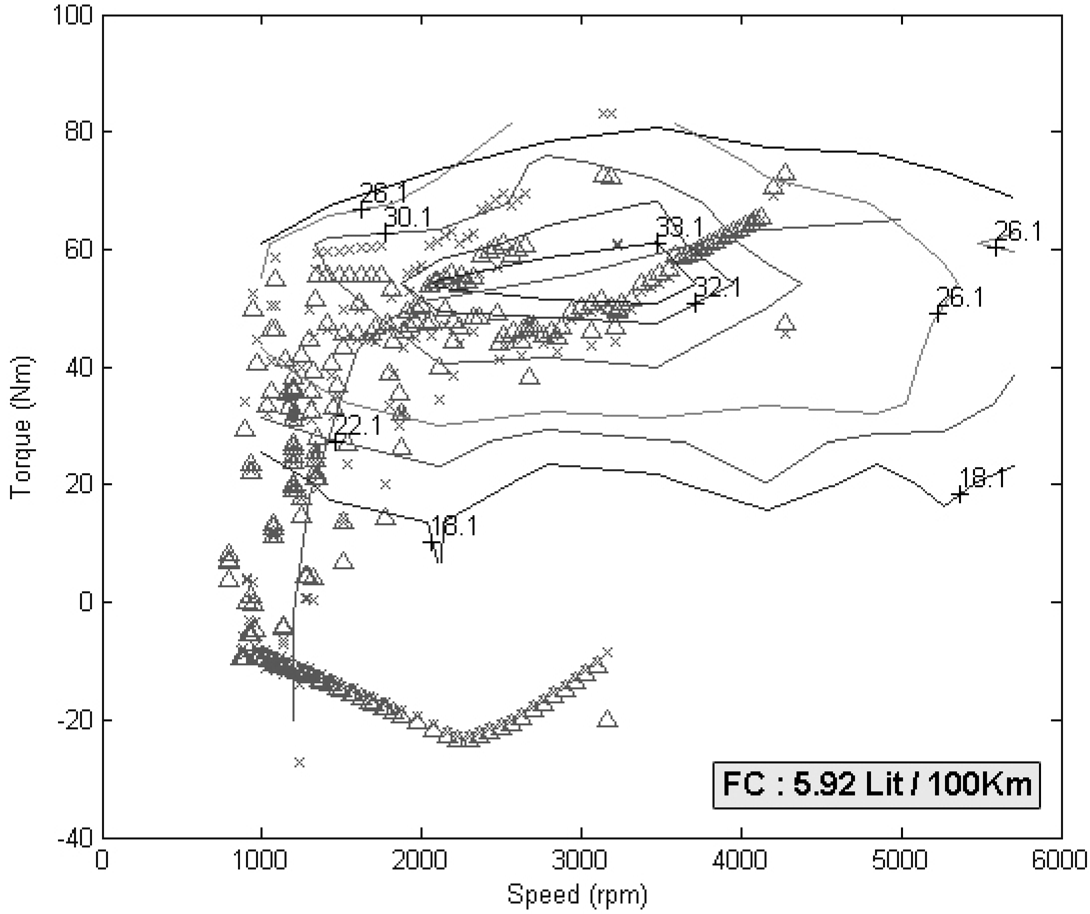

Figure 12. EOP placement of new strategy (5-speed MT)

7. Conclusion

A novel approach applicable to geared transmissions was introduced in order to achieve more fuel economy. As in the case of CVT, control of engine operating points plays a major role in the fuel consumption reduction, a many-gear transmission was assumed to perform similarly. Preliminary investigations showed that 14 intermediate gears would be satisfactory for the concept of virtual many-gear transmission.

Using a Fuzzy decision making system, shifting controller was developed to control the position of EOPs during every vehicle trip. Two first attempts to controlling the engine speed and also load in the range of fuel efficient area were found inadequate and did not lead to appealing results. In a new approach the effect of engine state was taken into consideration to meet the EOP efficient points together with engine fuel efficient curve as the target of EOPs for the controller.

The developed strategy was first applied to the virtual many-gear case with 16 gears. It was shown that the method was considerably successful in bringing EOPs close to EFCC curve while keeping engine output power range at lower values and in turn reducing fuel consumption. The strategy was then investigated in various simulations for conventional Manual and Automatic transmissions. Although the approach does not claim minimum possible fuel consumptions, it causes an evident improvement comparing with other applied strategies in account of proper combination of geared transmission efficiencies with economic shifting plan. The simulations showed improvements of the fuel economy by 4.3% in AT and 1.6% in Manual cases. It should, however, be pointed out that the design of shifting strategy in this work was only performed with respect to fuel economy and the vehicle performance was not focused.

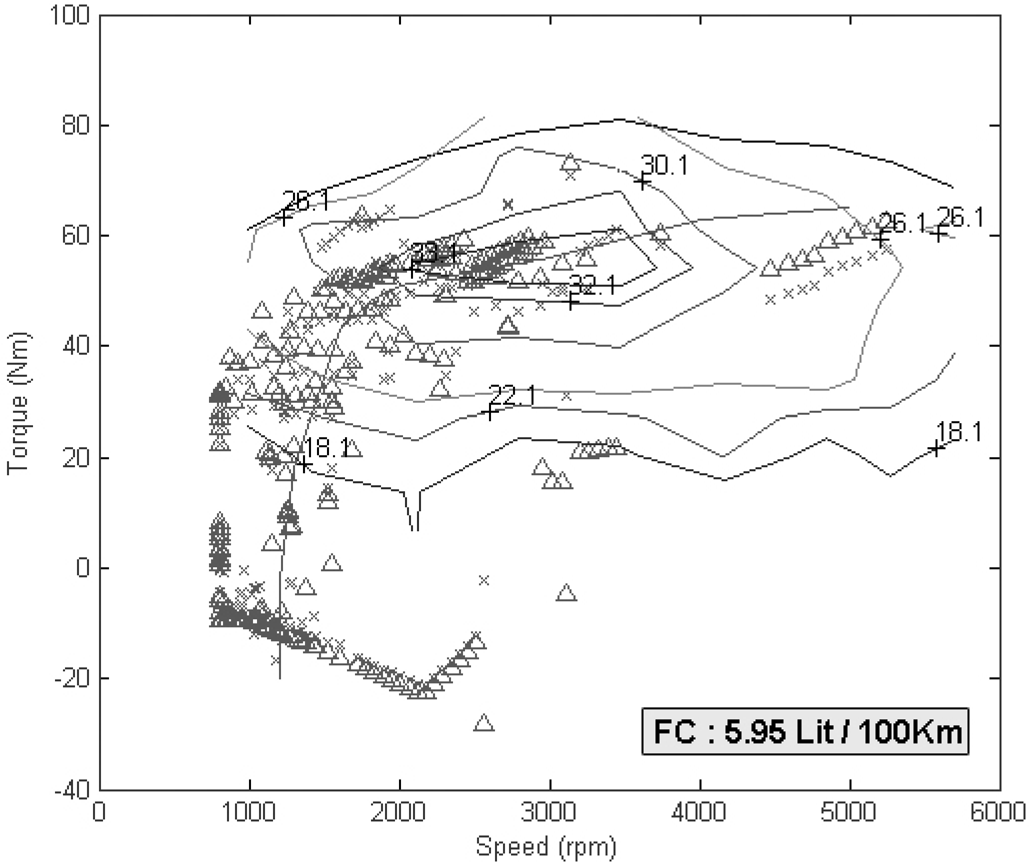

Figure 13. EOP placement of new strategy (4-speed AT)

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Notations and abbreviations

AMT	Automated Manual Transmission
AT	Automatic Transmission
CVT	Continuously Variable Transmission
EFCC	Efficient Fuel Consumption Curve

EOP	Engine Operating Point
FC	Fuel Consumption
ICE	Internal Combustion Engine
NEDC	New European Driving Cycle
SFC	Specific Fuel Consumption
$\alpha_{throttle}$	Throttle angle
T_e	Engine torque
$T_{\max}$	Engine maximum torque
ω	Engine rotation speed

Appendix: The vehicle data

Parameter	Value/specification
Vehicle mass	1120 Kg
Air Drag Coefficient	0.3
Frontal Area	1.72 m^2
Rolling Resistance Coefficient	0.009
Engine Type	Spark Ignition
Peak Power	70 kW @ 6000 rpm
Max. Engine Torque	138 Nm @ 3500 rpm
Manual Gearbox	
1st Gear Total Ratio	13.45
2nd Gear Total Ratio	7.57
3rd Gear Total Ratio	5.01
4th Gear Total Ratio	3.77
5th Gear Total Ratio	2.83
Final Drive Ratio	3.77
Automatic Gearbox	
1st Gear Total Ratio	8.96
2nd Gear Total Ratio	5.0512
3rd Gear Total Ratio	3.2956
4th Gear Total Ratio	2.4024
Final Drive Ratio	2.55

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