Powertrain Plus Driving Conditions Impact on Fuel Economy

MSc. Fernando Fusco Rovai
VW do Brasil / Centro Universitário FEI

ABSTRACT

Energy management and vehicle fuel economy are important automotive development drivers besides ambient emissions. Many technologies and solutions are being proposed, compared and improved. Any solution demands expensive resources to be tested and sometimes even the most accurate experimental arrangement is not enough to prove its effectiveness. In this scenario numerical simulation represents an important and reliable tool to make sure even very small improvements, very difficult to be measured, could be honestly compared. Considering that a vehicular solution could be more efficient depending on drive cycle this paper compares, by numerical simulations, the impact of vehicle powertrain plus driving conditions on a passenger car fuel economy. From powertrain side different transmissions, manual (5 and 6 speed) and automatic (6 speed: dual clutch, torque converter and CVT), are compared. From driving conditions side different test cycles (FTP75, HWY, NEDC and WLTC) and vehicle loads (unloaded 1000 kg vehicle and loaded 1500 kg vehicle) are compared.

INTRODUCTION

Vehicle fuel economy will always be an important research and development driver, besides emissions. Many variables affect vehicle fuel consumption. Some of these variables refer to vehicle concept and technology. Other variables depends on the way the vehicle is driven.

Hirano, Miller and Schneider [1] compared performance and fuel economy of different transmissions in the same vehicle on specific cycles and constant speeds. In this study the CVT efficiency was measured below 90 percent on electric dyno bench. CVT results were close to a 5 speed manual transmission on fuel consumption and much better than a 3 speed conventional automatic transmission.

Wagner, Remmlinger and Fischer [2] compared performance and fuel economy of a 6 speed conventional automatic to a continuously variable transmission in the same vehicle. In this study the continuously variable transmission resulted in better performance for the same vehicle fuel consumption.

Patel, Ely and Overson [3] studied continuously variable transmission variables like shift speed and torque converter lockup impact on performance feel.

Olmos, A. et. all [4] compared energy efficiency of a vehicle on different laboratory cycles and on real drive cycles.

Vehicle technologies are improving so fast. Regarding vehicle powertrain, many engines and transmissions combinations are possible. A conventional internal combustion engine can be combined to a variety of transmission concepts, from manual to automatic. These combinations result in different vehicle energy efficiency. The engine global efficiency map shows that energy conversion efficiency varies with engine speed and torque. This conversion efficiency is affected by combustion effects, friction, volumetric efficiency and component temperature limits.

The drive cycle the vehicle is driven, according to vehicle transmission, defines the instantaneous engine speed and torque, and consequently the vehicle energy consumption, at each cycle instant. Real life drive cycles have infinite possibilities, which are unviable to be reproduced. Many standard drive cycles were defined and adopted to represent and approach the real life.

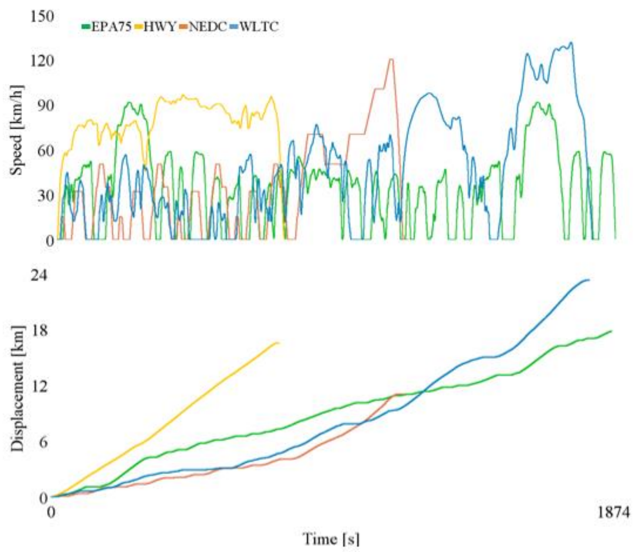

Figure 1. Simulated drive cycles comparison

Figure 1 shows the vehicle speed and displacement profiles along time of the four drive cycles simulated and compared in this study. Vehicle average power and engine average global efficiency varies with drive cycle.

The dynamic numerical 1-D simulation of a 5 speed manual transmission vehicle along the four drive cycles considered in this study resulted the operation points plotted in Figure 2. The operation points of each drive cycle are plot in a specific color. The plotted points demonstrate that engine is not used in its best efficiency on these drive cycles. As studied and demonstrated by Rovai [5], the best in-cycle fuel economy is achieved operating the engine in its best efficiency during accelerations (higher torque) but on lower engine speeds and efficiency during cruise and lower torque conditions.

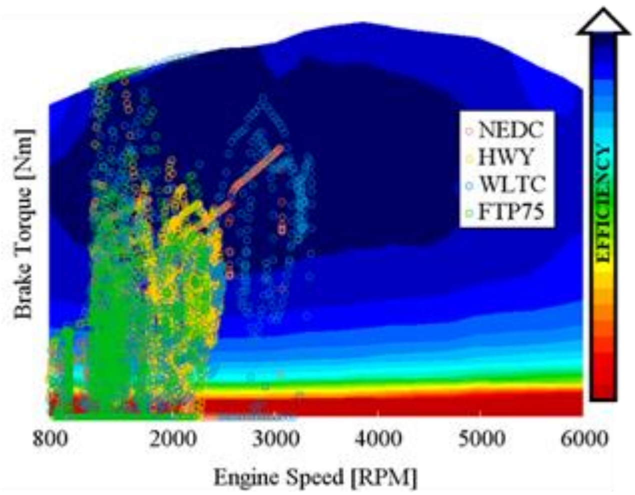

Figure 2. Engine in-cycle operating points

This paper compares the influence of the transmission concept on consumed fuel of a vehicle on different drive cycles for unloaded and loaded vehicle. The transmissions were simulated considering 100% efficiency. This comparison is possible through numerical simulation but it is considerable difficult, and expensive, to be done experimentally. Simulation absolute uncertainty is minored is this study because it is based on comparative results. The performed simulations assess the transmission concept influence on engine speed and torque and finally on vehicle fuel economy.

NUMERICAL SIMULATION

The GT-DRIVE® software from Gamma Technologies was used to perform the 1-D dynamic drive simulations. Figure 3 illustrates the main vehicle mathematical model. To assure the reliable comparison between simulation results the vehicle, engine, driver and ECU parts are exactly the same for all cases. The only differences considered were the transmission concept and its control unit (TCU).

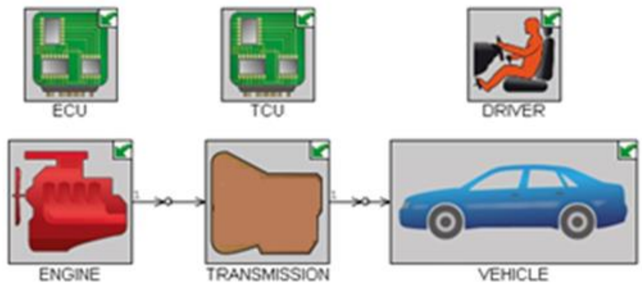

Figure 3. 1-D simulation GT-DRIVE® model

A compact passenger car was simulated considering the drag force coefficients in Table 1. Two vehicle mass were simulated, the unloaded (1000 kg) and the loaded (1500 kg) vehicle, according to NBR6601 inertia classes [6]. The vehicle load in practice affects drag force coefficients but in this study, for simplification, the same drag coefficients were considered for both vehicle loads.

Table 1. Vehicle drag coefficients

Vehicle mass	1000 / 1500	[kg]
F0	150	[N]
F2	0,04	[N/(km/h)^2]

This vehicle was equipped with a four stroke, spark ignition, naturally aspirated internal combustion engine. All the engine characteristics like torque curve, global efficiency map, idle speed and idle control were exactly the same for all simulated cases. This vehicle was simulated considering engine running and idle fuel consumption when vehicle is stopped. The hydraulic pump required by automatic transmissions were not considered in this study.

The simulated transmission concepts are:

- 5 gear dry clutch manual transmission (MC5)
- 6 gear dry clutch manual transmission (MC6)
- 6 gear dual clutch automatic transmission (DC)
- 6 gear torque converter automatic transmission (TC)
- Dual clutch continuously variable transmission (DC CVT)
- Torque converter continuously variable transmission (TC CVT)

Table 2 indicates the considered final transmission ratios as V1000 that means vehicle speed to each 1000 rpm engine speed. The 6th gear is added for all transmission concepts and the automatic transmissions were simulated only in this configuration. The gear ratios are exactly the same for all transmission concepts. The relation between the extreme gear ratios is defined as transmission ratio spread. The CVT transmission was simulated with the same transmission ratio spread of the 6 gear versions, varying linearly from the 1st do the 6th gear ratio. Higher gear ratio spreads could improve both fuel economy and ramp gradeability.

Table 2. Vehicle speed per gear ratio and engine speed

5-gear [gear]	6-gear [gear]	CVT [ratio]	V1000 [km/h]
1	1	min	7,0
2	2		12,6
3	3		20,5
4	4		29,8
5	5		39,0
	6	max	47,2

Gear shift strategy is a very significant variable for fuel consumption. The simulated shift strategy follows the gear shift indicator (GSI), studied by Rovai [5], and extended to 6^{th} gear in this study, as shown in Figure 4.

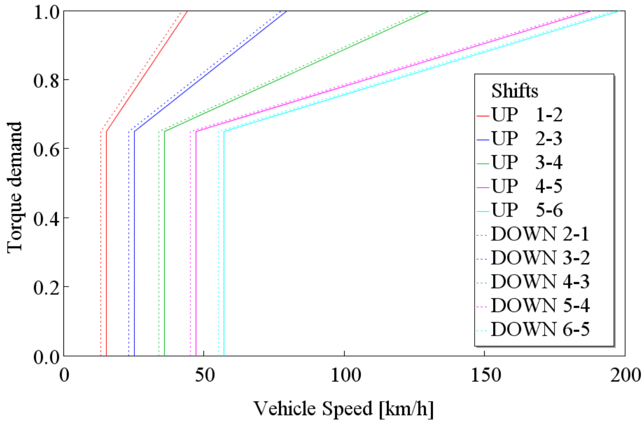

Figure 4. Shift strategy for 5 and 6 gear concepts

Despite the standard defined shift points of NEDC, the optimized GSI shift strategy was considered even on NEDC simulated cycle in this study in order to compare the four drive cycles in its best vehicle efficiency.

The gear shift time, which affects slightly fuel economy, was adjusted in 1 second for manual transmissions and in 0,5 second for automatic transmissions.

Continuously variable transmission concepts follows the same GSI strategy in terms of fuel consumption optimization. In this transmission concept the shift speed is defined or limited by a time constant. Figure 5 shows the shift strategy applied to continuously variable transmissions. Differently from Figure 4, in Figure 5 the gear ratio varies linearly and continuously between the extremes.

The continuously variable transmission shift speed was represented in this study by the shift time constant. Three different time constants of 1, 2 and 5 seconds were compared in this study. Higher time constants implies in lower transmission shift speed as shown in Figure 6.

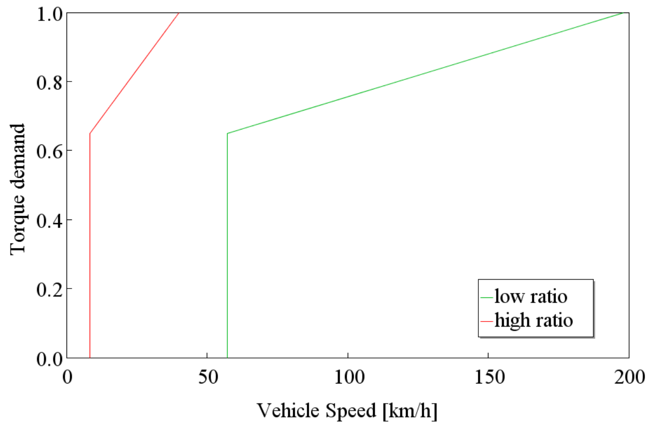

Figure 5. Shift strategy for CVT concepts

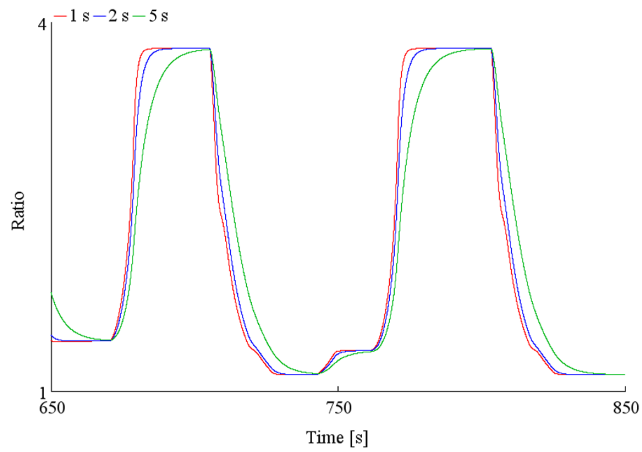

Figure 6. Simulated CVT shift speed time constants

The performed simulations consider neutral gear for vehicle stopped with brake pedal pressed. This definition is important to avoid fuel consumption penalty in this condition for the concepts equipped with torque converter.

The torque converter adopted in some automatic transmission concepts was simulated based on two characteristics [7]: the capacity factor (K_{CAP}) that is a torque and speed relationship and the torque ratio (K_{TR}) that is a transmission and engine torque relationship, according to Equations 1 and 2, respectively:

$$K_{CAP} = \frac{w_{ENG}}{\sqrt{T_{ENG}}} \tag{1}$$

$$K_{TR} = \frac{T_{TRANS}}{T_{ENG}} \tag{2}$$

where:

w_{ENG} = engine speed output [RPM]
T_{ENG} = engine torque output [Nm]
T_{TRANS} = transmission torque input [Nm]

The combination of capacity factor and torque ratio defines the torque converter behavior in terms of torque response and drive comfort. Two extreme torque converters were simulated from intermediate capacity factor and torque ratio values. The HARD torque converter was defined with twenty five percent lower capacity factor and twenty five percent higher torque ratio from intermediate values, which resulting in better drive response. The SOFT torque converter was defined with twenty five percent higher capacity factor and twenty five percent lower torque ratio from intermediate values, resulting in better drive comfort. These proposals are illustrated in Figure 7.

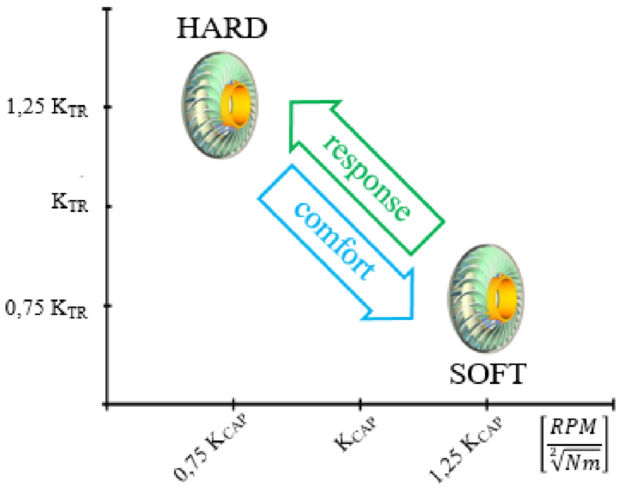

Figure 7. Simulated torque converter behavior

The dynamic response of these two simulated torque converters is shown in Figure 8. During extra urban phase of NEDC cycle, for example, the SOFT torque converter (in red) is much more slippery than the HARD torque converter (in blue) during vehicle accelerations. The comparison shown in Figure 8 was simulated without lockup for better demonstration.

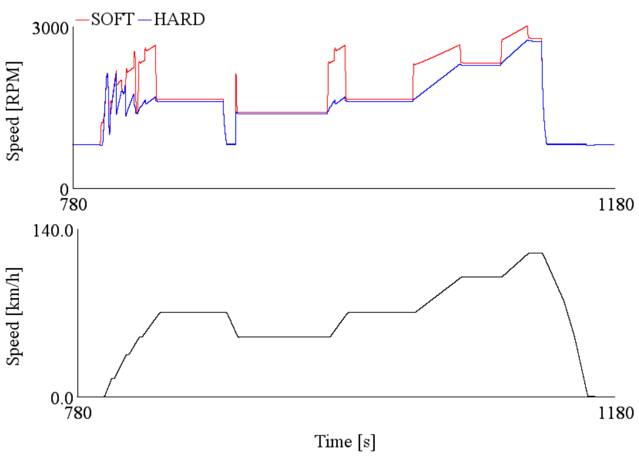

Figure 8. Torque converter dynamic response

The lockup strategy is another important variable for torque converters. This strategy avoids the torque converter to slip above a defined engine speed. This study simulated the impact of three lockup speeds: 1200, 1500, 1800 rpm and a lockup off condition in which lockup was disabled.

The design of experiments of the performed simulations are detailed in Figure 9. These simulations were performed for unloaded (1000 kg) and loaded (1500 kg) vehicle on FTP75, HWY, NEDC and WLTC drive cycles resulting in 304 simulations.

The fuel consumption is numerically integrated along drive cycle in steady-state steps. Cold phase impact was not considered in this study.

Gearset	Clutch	Torque Converter	Lockup [rpm]	CVT time constant [s]
5	MC			
6	MC			
	DC			
	TC	SOFT	1200	
			1500	
			1800	
			OFF	
		HARD	1200	
			1500	
			1800	
			OFF	
CVT	DC			1
				2
				5
	TC	SOFT	1200	1
				2
				5
			1500	1
				2
				5
			1800	1
				2
				5
			OFF	1
				2
				5
		HARD	1200	1
				2
				5
			1500	1
				2
				5
			1800	1
				2
				5
			OFF	1
				2
				5

Figure 9. Simulation DOE

RESULTS AND ANALYSIS

TORQUE CONVERTER IMPACT ON FUEL ECONOMY

The SOFT and HARD versions of torque converter and its lockup impact on fuel consumption, for both unloaded and loaded vehicle, are shown on Figures 10 to 13. The lockup speeds were simulated in 1200, 1500 and 1800 engine rpm and in the worst case lockup was turned off.

The simulated cycles resulted in low vehicle load influence on fuel consumption for HARD torque converter. The penalty on fuel economy of SOFT torque converter increases with lockup speed. This behavior makes sense because the lower lockup speeds reduces significantly the torque converter slip, which is more significant in SOFT version.

While HWY and NEDC cycles presented around maximum 15 percent penalty on fuel consumption, FTP75 and WLTC presents higher than 25 percent for SOFT version. These results demonstrates that more dynamic drive cycles in terms of accelerations and gear shifts are more affected by torque converter slip and lockup speed. The simulations resulted in considerable higher impact of SOFT torque converter on loaded vehicle, especially for 1800 rpm converter lockup and lockup off, which was not too significant with HARD torque converter.

The fuel economy results are slightly better with SOFT torque converter for 1200 rpm lockup. Specifically on low engine speed conditions the more slippery torque converter resulted in better engine efficiency and lower fuel consumption.

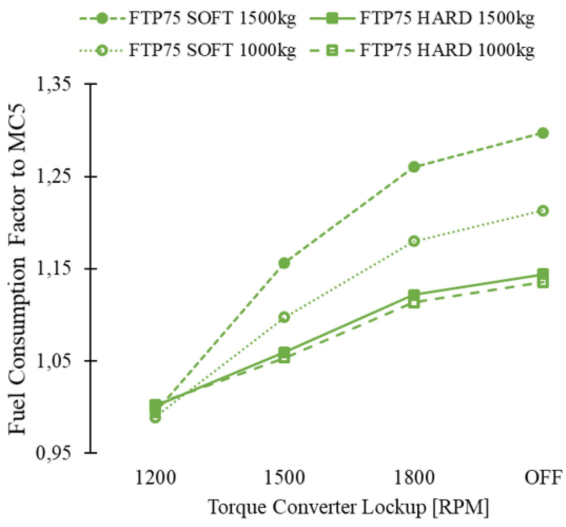

Figure 10. Torque converter impact on FTP75

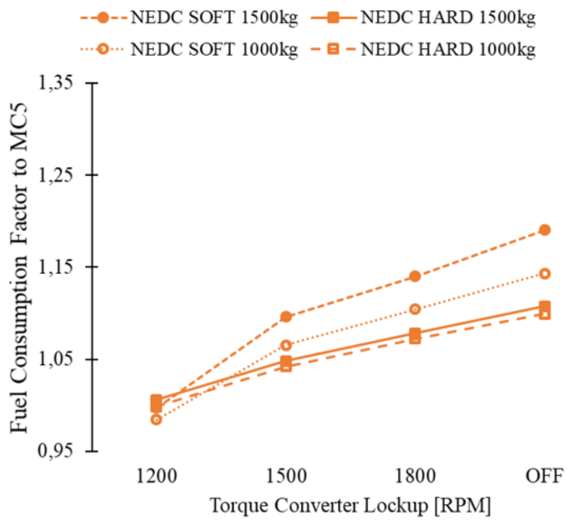

Figure 12. Torque converter impact on NEDC

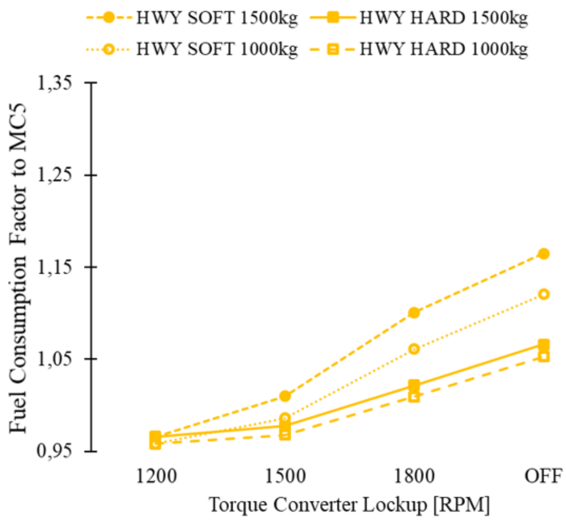

Figure 11. Torque converter impact on HWY

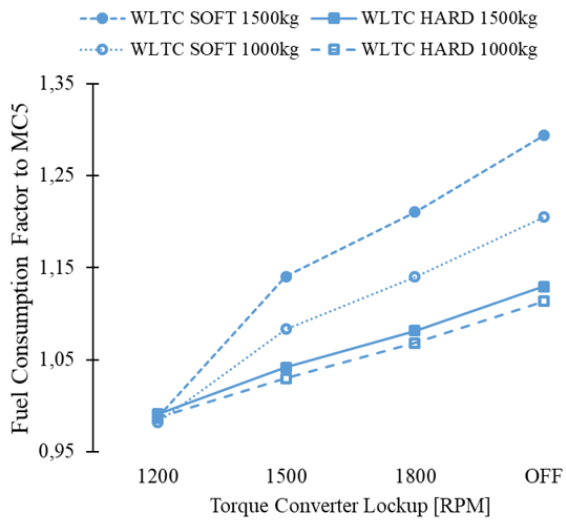

Figure 13. Torque converter impact on WLTC

CVT SHIFT SPEED IMPACT ON FUEL ECONOMY

The impact of CVT shift speed time constant on fuel consumption is shown from Figure 14 to Figure 21. The unloaded vehicle results are presented on the left and the loaded vehicle results on the right for any drive cycle.

The time constant of 1, 2 and 5 seconds impact are presented for the simulated drive cycles. The simulated clutch (DC, SOFT and HARD torque converters) and lockup (1200, 1500, 1800 rpm and lockup off) of CVT configurations are plotted.

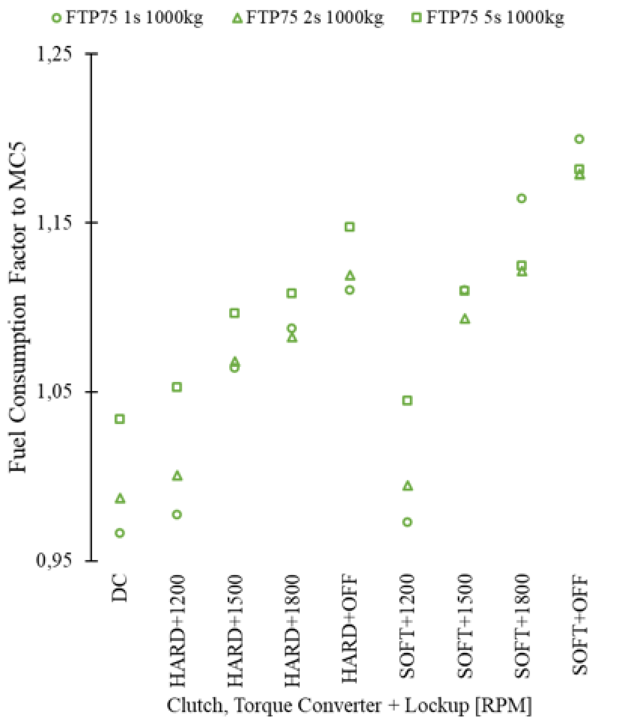

Figure 14. Time constant impact on unloaded FTP75

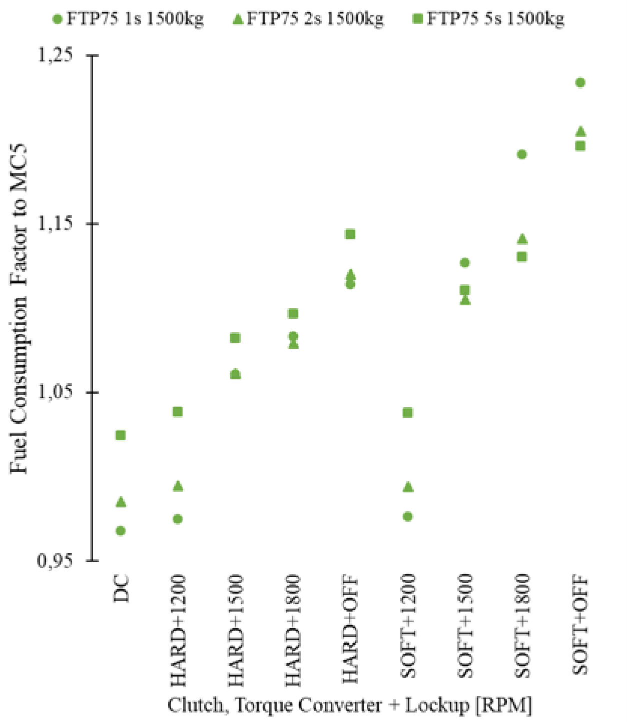

Figure 16. Time constant impact on loaded FTP75

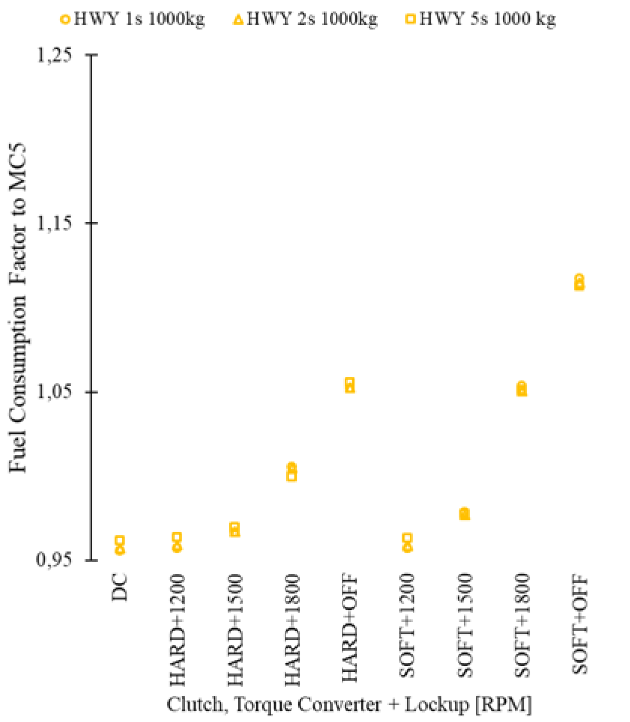

Figure 15. Time constant impact on unloaded HWY

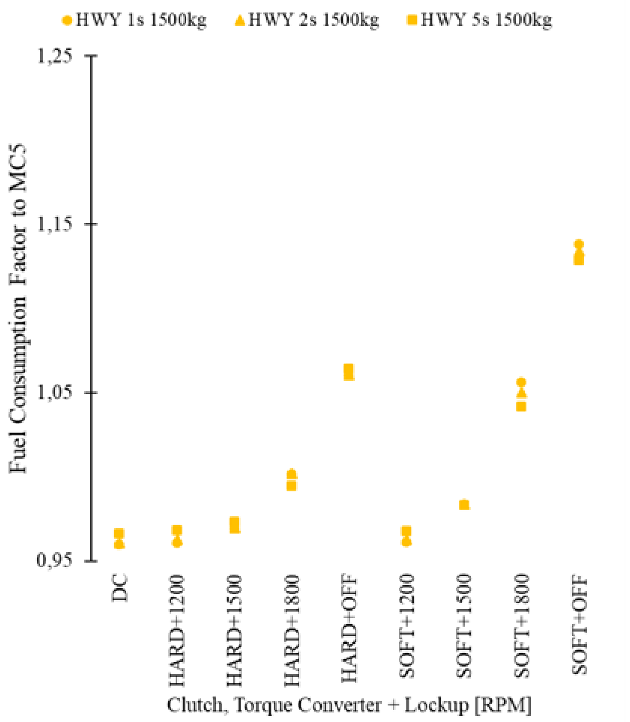

Figure 17. Time constant impact on loaded HWY

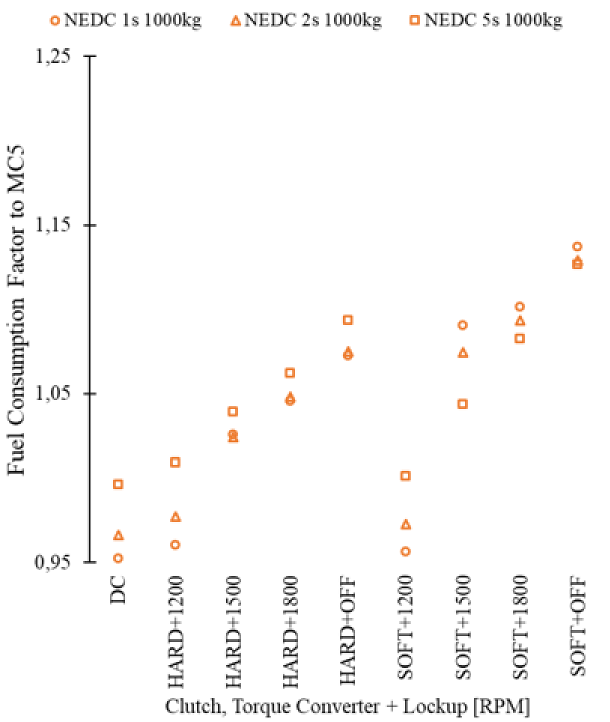

Figure 18. Time constant impact on unloaded NEDC

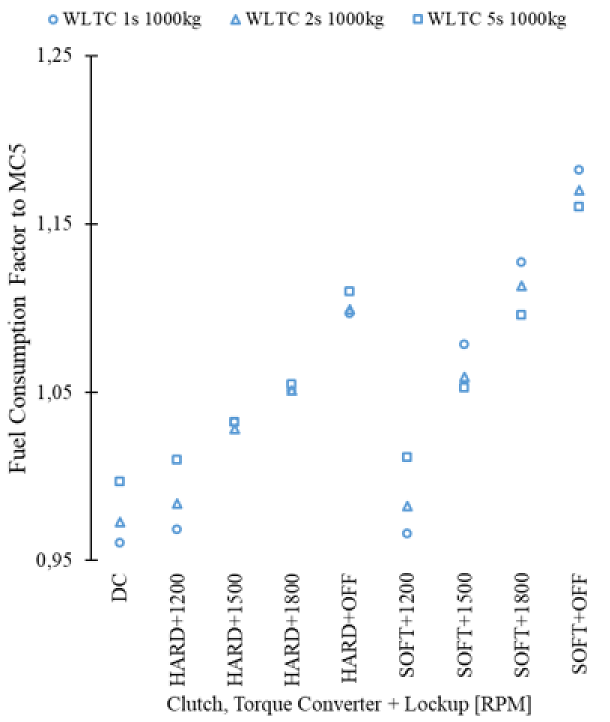

Figure 19. Time constant impact on unloaded WLTC

The results show quite similar shift speed time constant influence on the simulated drive cycles for the two vehicle load conditions.

The lowest time constant impact occurred in HWY that is a cycle with more constant speeds and mostly performed at lowest transmission ratio.

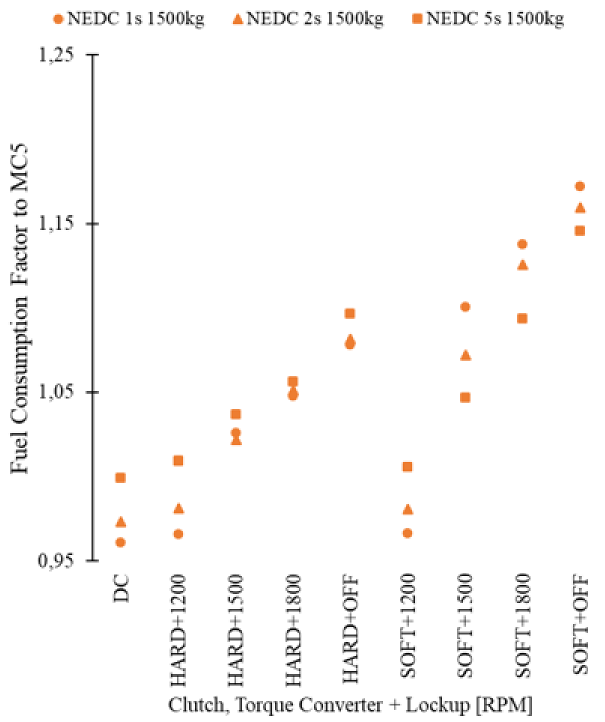

Figure 20. Time constant impact on loaded NEDC

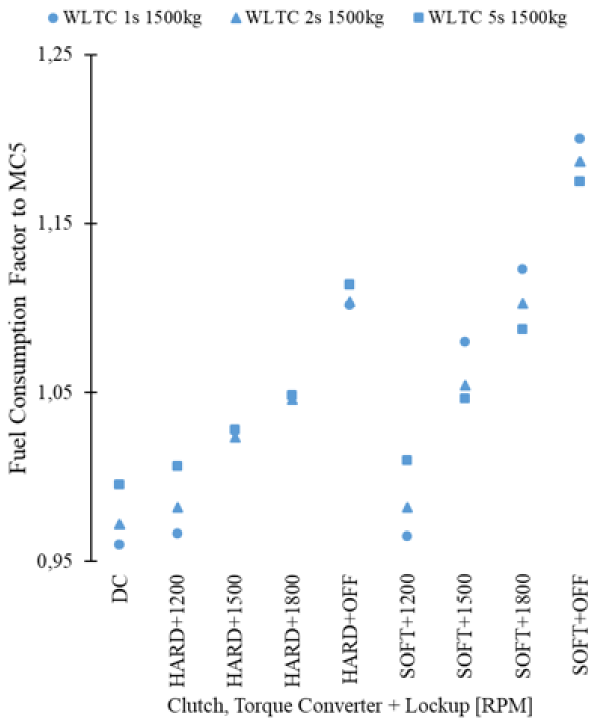

Figure 21. Time constant impact on loaded WLTC

On the other cycles, more dynamic than HWY, higher time constant increases fuel consumption especially and linearly for DC with 1200 rpm lockup.

Higher lockup engine speeds are less sensitive to CVT shift speed time constant.

Torque converter characteristics, SOFT or HARD, presented similar penalty on fuel economy for the simulated time constants and vehicle loads.

Lockup speed influence is noticeable in all cycles and conditions but more significant for SOFT torque converter.

The best results were verified with DC clutch and 1 second shift speed time constant. The results of SOFT and HARD torque converters with 1200 rpm lockup are quite similar and slightly higher than the results with DC. Sometimes the SOFT torque converter presented better efficiency than HARD version with 1200 rpm lockup, similarly as observed and explained with torque converter automatic transmission, but less pronounced due to CVT transmission ratio variation during vehicle accelerations.

DRIVE CYCLE IMPACT ON FUEL ECONOMY

Figure 22 shows the comparative results for unloaded vehicle (1000 kg). All the results are relative to MC5 version. The reduction on fuel consumption of a 6th gear is evident and more pronounced on HWY due to higher cycle speeds in which 6th gear ratio are mostly used. The dual clutch configuration is more economical than manual clutch due to its lower shifting time and reduced engine speed during clutch modulation. The torque converter versions could achieve reduction on fuel consumption similar to manual clutch when adopting 1200 rpm lockup. But with SOFT torque converter and higher lockup speeds the penalty on fuel economy are very significant, mainly on more dynamic drive cycles, achieving up to 22 % higher fuel consumption. The best result was achieved with dual clutch and CVT with one second shift speed time constant. The SOFT torque converter and the higher lockup speeds affect CVT negatively, resulting in up to 20% higher fuel consumption.

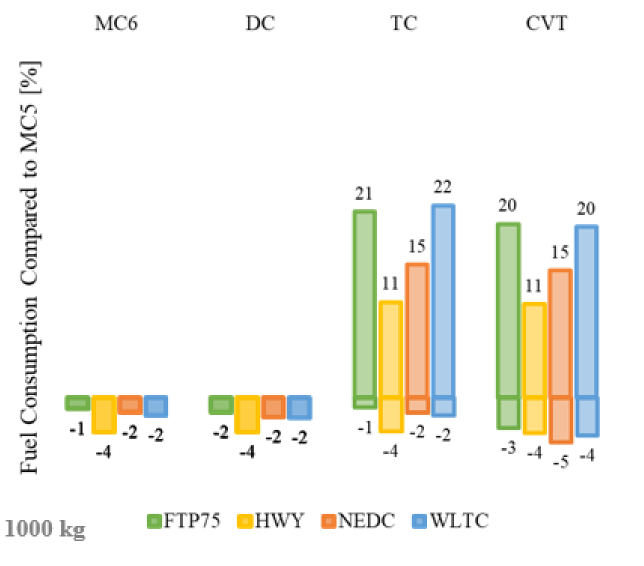

Figure 22. Fuel economy impact on unloaded vehicle

The results for loaded vehicle (1500 kg) are shown on Figure 23. The dual clutch CVT advantage are more significant in this condition. The six gear transmissions require downshifts to the 5th or lower discrete gears while CVT could run on intermediate, and more efficient, gear ratios. The SOFT torque converter and higher lockup speeds impacts are more pronounced for loaded vehicle. The more dynamic cycles, FTP75 and WLTC, presented more variations due to frequent vehicle accelerations and downshifts.

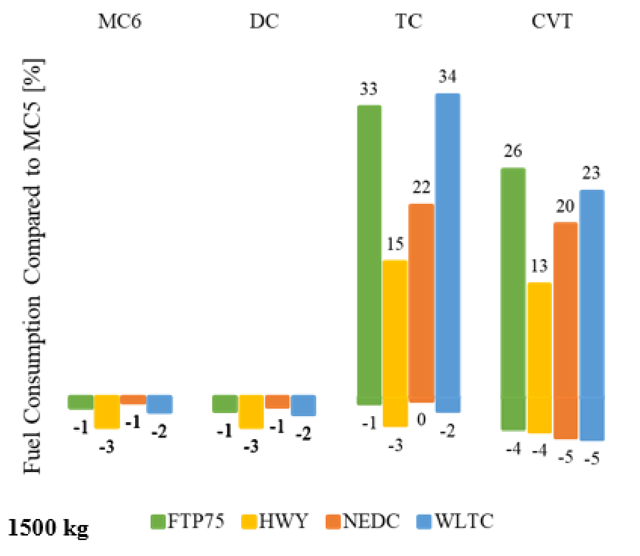

Figure 23. Fuel economy impact on loaded vehicle

Another analysis regarding drive cycle and vehicle load influences is shown on Table 3. As the best results in terms of fuel economy were achieved with unloaded vehicle on HWY this condition was adopted as reference for any transmission concept.

The worst and the best results of torque converter automatic transmissions (TC) are presented. For these applications the best results were achieved with 1200 rpm lockup and the worst results were achieved with SOFT torque converter and lockup off. The continuously variable transmissions with faster shift speed presented the best results with dual clutch (DC CVT). Continuously variable transmission coupled to torque converter (TC CVT) presented better results for 1200 rpm lockup and worse results for SOFT torque converter and lockup off.

Table 3 presents the highest fuel consumption in WLTC for any vehicle load and transmission configuration. The vehicle load impact on HWY is much lower than in the other cycles. DC CVT presents some advantage over the best TC CVT only on FTP75 and unloaded vehicle and on WLTC and loaded vehicle. Torque converter slip and lockup impacts are confirmed on FTP75 and WLTC cycles, pronounced on loaded vehicle.

Table 3. Fuel consumption factors

Vehicle Transmission	1000 kg			
	HWY	FTP75	NEDC	WLTC
MC5	1	1,10	1,17	1,18
MC6	1	1,13	1,20	1,21
DC	1	1,13	1,20	1,21
TC (best)	1	1,14	1,20	1,21
TC (worst)	1	1,19	1,19	1,27
DC CVT (best)	1	1,11	1,17	1,19
TC CVT (best)	1	1,12	1,17	1,19
TC CVT (worst)	1	1,18	1,19	1,25
Vehicle Transmission	**1500 kg**			
	HWY	FTP75	NEDC	WLTC
MC5	1,03	1,22	1,26	1,29
MC6	1,03	1,26	1,31	1,33
DC	1,03	1,26	1,31	1,33
TC (best)	1,03	1,27	1,31	1,33
TC (worst)	1,07	1,41	1,34	1,49
DC CVT (best)	1,03	1,24	1,27	1,29
TC CVT (best)	1,03	1,24	1,27	1,30
TC CVT (worst)	1,04	1,35	1,32	1,38

AVERAGE ENGINE SPEED AND TORQUE ANALYSIS

It is difficult to compare all the engine operating points along drive cycle on the engine map, as shown on Figure 2. Alternatively, the average of in-cycle engine speed and torque can be precisely positioned on engine map.

The simulated engine speed and torque averages are located in a narrow engine global efficiency region shown inside white dotted lines on Figure 24.

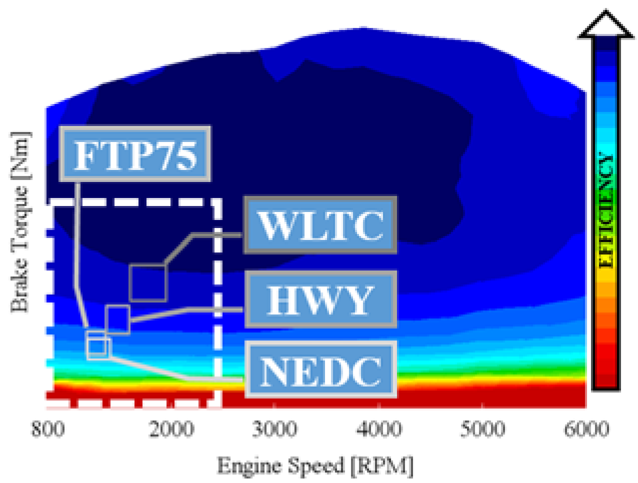

Figure 24. Average simulation results on engine map

Average engine speed and torque for unloaded and loaded vehicle of simulated cycles are placed inside rectangular cycle envelopes indicated on Figure 24. FTP75 and NEDC engine speed and torque average envelopes are the lowest ones. HWY cycle demands intermediate average engine speed and torque envelope and WLTC represents the highest envelope in terms of engine speed and torque averages. According to the engine efficiency scale of Figure 24 the simulated cycles are outside the best engine efficiency condition.

The average envelopes for the simulated cycles are detailed from Figure 25 to Figure 28. The TC CVT best configuration presented on Table 3 is not considered in this analysis. The transmission configurations are plotted with different marker type. The MC6, DC, TC and CVT best options are plotted in green lines and its worst options are plotted in red lines. Simulations of loaded vehicle (1500 kg) are plotted in gray filled marks and the unloaded vehicle (1000 kg) results are plotted in white filled marks.

FTP75 results in Figure 25 shows a clear difference between unloaded and loaded vehicle. The MC5 version presented higher average engine speeds due to the narrow transmission ratio spread. The DC CVT resulted in lowest average engine speeds. The worst CVT results has higher average engine speed and slightly lower average engine torque than the best ones. The MC6, DC and the best TC transmissions average engine speeds do not change with vehicle load. The CVT and the worst TC versions runs on higher average engine speeds for higher vehicle loads. The better results of DC CVT presented on Figures 22 and 23 are explained by lower average engine speeds on Figure 25.

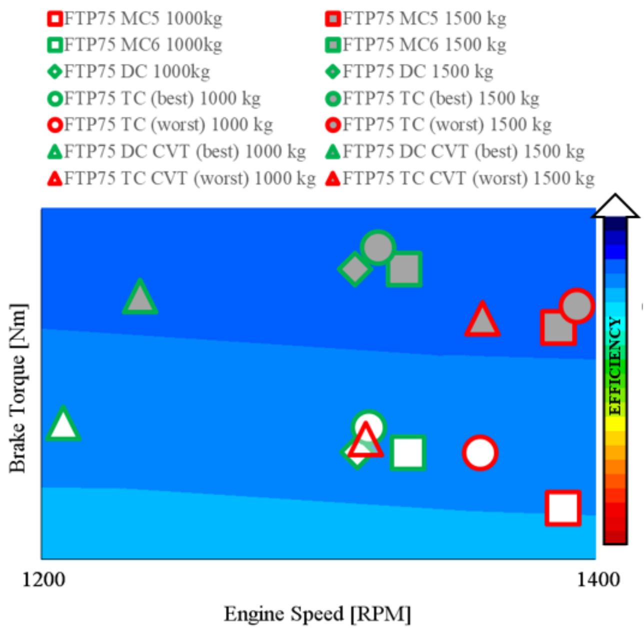

Figure 25. FTP75 averages envelope

HWY results are plotted in Figure 26. In this drive cycle the transmission ratio spread makes big difference. The MC5 transmission runs on considerable higher engine average speeds. Even the worst TC and CVT options could run in lower engine average speeds than MC5. The best configurations for fuel consumption presented quite the same average engine speeds. Some difference was noticed on loaded vehicle in which the DC CVT could run on low average engine speed than DC and TC configurations. The worst TC and CVT configurations presented the lowest penalty on fuel economy than in the other drive cycles. It can be explained by the more constant speeds and consequently less influence of torque converter slip.

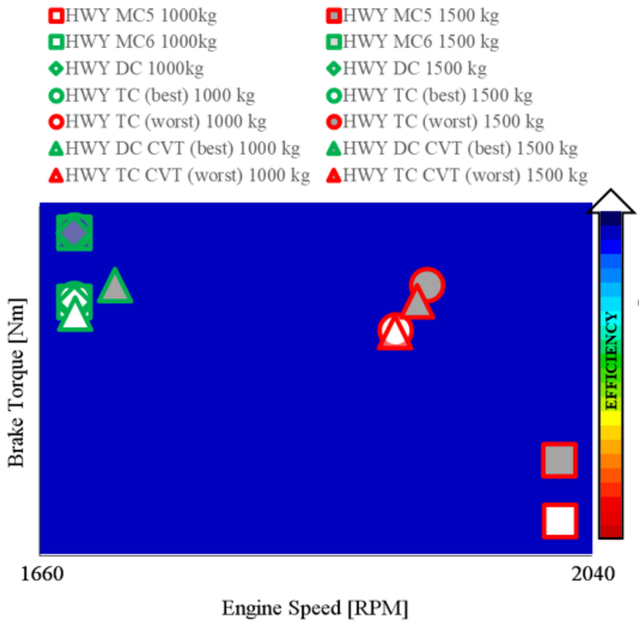

Figure 26. HWY averages envelope

NEDC results are presented in Figure 27. This drive cycle resulted on largest DC CVT advantages. As observed on FTP75, on NEDC the engine average torque difference is clear between unloaded and loaded vehicle. The MC5 reduced transmission ratio spread impact is increased by the extra urban phase.

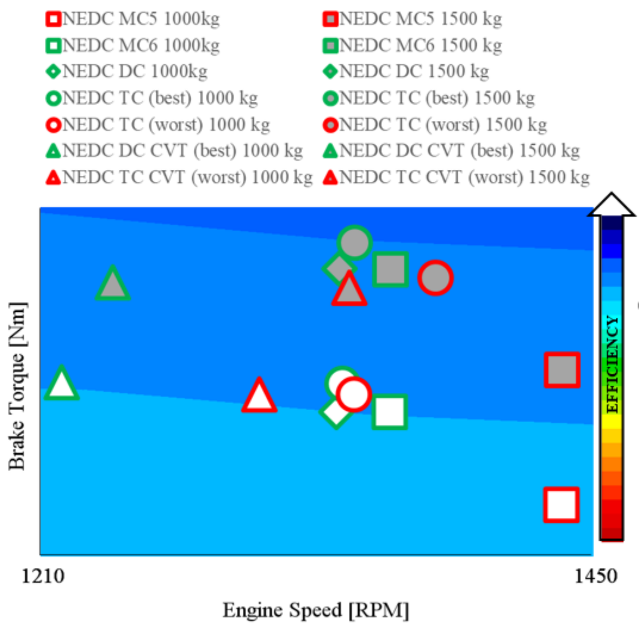

Figure 27. NEDC averages envelope

In NEDC cycle the worst CVT configurations are close to the best TC, DC and MC6 options. The DC CVT could perform the cycle in considerable lower average engine speed. The disadvantage of the worst TC and CVT results in this drive cycle is narrow than the disadvantage verified in FTP75 and WLTC cycles.

WLTC results are presented in Figure 28. This cycle demands more dynamic accelerations, high vehicle speeds and downshifts than the other simulated cycles. In these conditions the DC CVT presented significant advantage. The torque converter slip influence is similar in WLTC and in FTP75. The higher average engine speed of MC5 applications, due to its lower transmission ratio spread, is evident. The vehicle load impacts more significantly MC6, DC and TC engine average torque than any CVT.

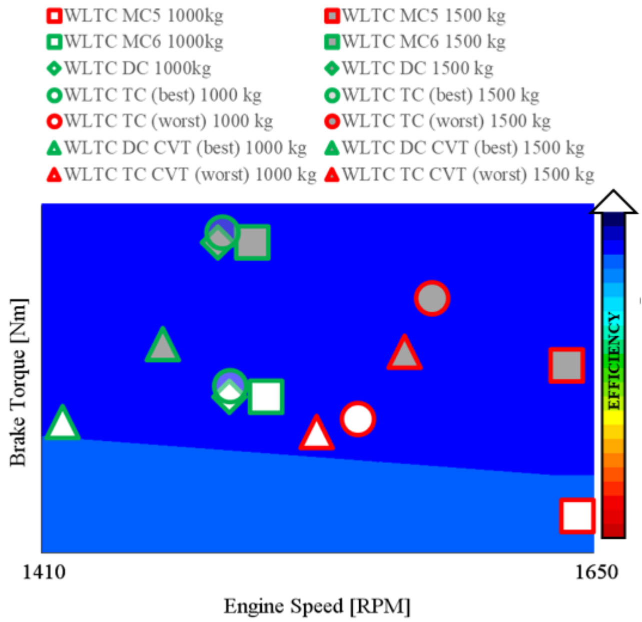

Figure 28. WLTC averages envelope

CONCLUSIONS

The results confirm that vehicle fuel economy is significantly affected by many variables: vehicle load, drive cycle and powertrain configuration. The powertrain configuration is defined by the internal combustion engine and the transmission configuration, which determines the engine operating point on its efficiency map along the drive cycle. The integration of the instantaneous engine fuel consumption along the drive cycle results in calculated in-cycle fuel economy. The objective of this study is to compare the influence of these different variables on the efficiency of exactly the same vehicle, which is almost impossible experimentally. The transmission efficiency differences, according to Naunheimer, H. et. all [8], were not considered in this study.

Numerical simulations pointed up to 5% fuel economy increasing transmission ratio spread, which can be achieved adding a 6^{th} gear in a conventional five speed gearbox. Expressive 24% reduction in fuel consumption can be obtained using a less comfortable torque converter in an unloaded vehicle. The economy provided by the torque converter characteristic could increase up to 36% in a loaded vehicle. Continuously variable transmissions are expected to achieve the best fuel economy results due to probable higher engine residence time around the best efficiency region of the map. The CVT shift speed limitation does not allow the engine to run continuously on its best efficiency along a dynamic drive cycle. In this study, the CVT shift speed was simulated varying time constant from 1 to 5 seconds, which represented about 6% penalty in fuel consumption.

Except for the fastest simulated CVT shift speed, there was no very significant fuel economy advantages of a continuously variable transmission over an optimized six gear automatic transmission in this study.

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ABOUT THE AUTHOR

MSc. Eng. Fernando Fusco Rovai. Mechanical Engineer and Master in Mechanical Engineering from Escola Politecnica da USP, São Paulo, Brazil. More than 20 years' experience working in research, development and calibration of engine electronic control systems. Currently works on numerical simulation focused on performance, energy efficiency and emissions reduction at Volkswagen do Brasil. Professor in undergraduate and specialization courses at Centro Universitário FEI. Internal combustion engine and calibration instructor at AEA. Contacted by: fusco800@hotmail.com

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DEFINITIONS / ABBREVIATIONS

CVT	Continuously Variable Ratio Automatic Transmission
FTP75	EPA75 Federal Test Procedure
HWY	EPA Highway Fuel Economy Test
NEDC	New European Driving Cycle
WLTC	Worldwide Harmonized Light Vehicles Test Cycles
ECU	Engine Control Unit
TCU	Transmission Control Unit
MC5	5 gear Manual Clutch and Transmission
MC6	6 gear Manual Clutch and Transmission
DC	Dual Clutch on Automatic Transmission
TC	Torque converter on Automatic Transmission
DC CVT	Dual Clutch on a CVT
TC CVT	Torque Converter on a CVT
V1000	Vehicle Speed per 1000 rpm Engine
GSI	Gear Shift Indicator
HARD	Torque Converter for Better Drive Response
SOFT	Torque Converter for Better Drive Comfort
DOE	Design of Experiments