

A DFSS Approach to Determine Automatic Transmission Gearing Content for Powertrain-Vehicle System Integration

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ABSTRACT

This investigation utilizes a DFSS analysis approach to determine automatic transmission gear content required to minimize fuel consumption for various powertrain - vehicle systems. L18 and L27 inner arrays with automatic transmission design and shift pattern constraint parameters were varied to determine their relative influence on fuel consumption. An outer noise array consisting of two vehicles with various engines, final drive ratios and legislated emissions test cycles was used to make a robust transmission selection based on minimizing fuel consumption. The full details of the DFSS analysis method and assumptions are presented along with a detailed examination of the results. With respect to transmission design parameters, parasitic spinloss and gear mesh efficiency were found to be most important followed by the number of gears. The DFSS analysis further revealed that unique transmission design formulations are potentially required for widely varying engines. The shift pattern constraint of minimum operating speed in gear that establishes the downshift line was found to be most significant while all other shift parameters proved to be negligible. An average 0.4 to 0.8% decrease in fuel consumption could be realized by optimizing the transmission for a given engine - vehicle combination with the underlying assumptions of the energy analysis. For a given transmission - vehicle, changing the engine resulted in an average 2 to 5% reduction in fuel consumption depending on the specifics of the engine technology.

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INTRODUCTION

The EPA's final rule mandating a reduction in greenhouse gas (GHG) emissions from a MY 2016 CAFE level of 250 g CO₂/mile (35.5 mpg) to MY 2025 level of 163.5 g CO₂/mile (54.5 mpg), see [1], has prompted focused effort by automotive OEM's and suppliers alike on powertrain - vehicle system integration for energy efficiency. Industry mega-trends for conventional vehicles to achieve these aggressive standards include light-weighting [2], road load reductions through tires and aerodynamics, engine downsizing, friction reduction, highly integrated air charging systems, [3] and advanced low parasitic loss automatic transmissions, [4 and 5]. Combining all of these technologies without substantially increasing the cost of the end vehicle while still achieving all customer expected and regulated performance metrics is the challenge. For successful integration in a reduced time window, without large capital investments in prototypes, energy analysis techniques such as those reported by [6 and 7] are required to be coupled with statistics based methodologies that seek to optimize the system in the face of a multi-factorial response. A number of such studies have been performed, such as the one by [8] in which the powertrain - vehicle system was explored for

efficiency improvements through integration of advanced technologies using statistical techniques and energy analysis methods.

Design for six sigma (DFSS) is a methodology used in product development aimed at increasing the robustness and efficiency of a process or design, see [9] for more details. The application of DFSS is most appropriate when applied to a process or design that does not yet exist. Based on these suppositions, a DFSS approach should harmonizes well with the objectives of powertrain - vehicle technology matching to optimize for fuel economy as suggested by the study conducted by [10] for transmission efficiency and robustness. The goal of this investigation is to present a DFSS approach to powertrain - vehicle system integration with the objective of reducing fuel consumption. The focus will be on design parameters and shift pattern constraints of the torque converter automatic transmission and defining those that are most influential on fuel consumption. A number of hypothetical planetary automatic transmission designs were created and combined with current production gasoline engines and vehicles to execute the DFSS study. This investigation is not meant to be an exhaustive investigation of advanced powertrain - vehicle technology integration as conducted by [9], but a presentation of the potential in utilizing the DFSS approach to matching the design

and operating characteristics of the automatic transmission to various engines and vehicles. The parameter diagram of Figure 1 summarizes the scope of the DFSS study to be detailed in this paper.

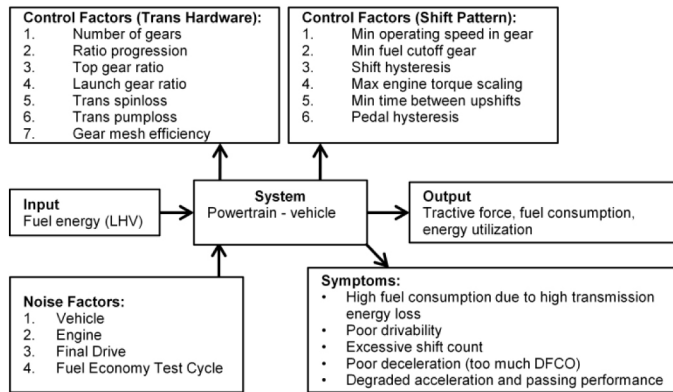


Figure 1. Parameter diagram for DFSS investigation into automatic transmission gearing content and powertrain - vehicle integration.

DFSS AND ENERGY ANALYSIS SETUP

Two different DFSS studies will be presented that focus on determining what are the most influential automatic transmission design parameters and shift pattern constraints that lead to the best fuel economy. The details of the transmission parameters, vehicles, engine and test schedules used and the assumptions associated with the DFSS study are detailed in the following sections. It should be noted that all the automatic transmission combinations contained in this study are hypothetical and thus are paper transmissions.

L18 Inner Array - Automatic Transmission Design Parameters

The first DFSS study utilizes an L18 inner array matrix that contains 18 unique combinations of transmission design parameters with one parameter at six different levels and six parameters each at three levels. The L18 is an orthogonal array with interactions between parameters well distributed throughout the array. Table 1 summarizes the automatic transmission design parameters and their levels used in the L18 inner array. Appendix A contains the full coded and un-coded variable layout of the L18 array used in this investigation.

Table 1. Summary of automatic transmission hardware parameters used for L18 inner array.

Parameter		Level					
A	Number of Gears	6	8	9	10	12	14
B	Ratio Progression	Geometric		Linear		Log Decay	
C	Top Gear Ratio	0.6	0.7	0.8			
D	Launch Gear Ratio	4.25	4.75	5.25			
E	Trans Spinloss	-30%	Nom	+30%			
F	Trans Pumploss	-30%	Nom	+30%			
G	Gear Mesh Efficiency	Nom	-1%	-2%			

Number of Gears and Ratio Progressions

The current state of planetary automatic transmissions for passenger and light duty applications has seen a very rapid increase in number of forward gear states from 6 first introduced in 2003, [11], to 8 in 2009, [4], and more recently 9 in 2013, [5]. To capture this trend and beyond, transmissions with 6, 8, 9, 10, 12 and 14 forward gear states are considered for the L18. Figure 2 contains an example of each unique speed transmission used in the L18 array with a launch (1st) gear ratio of 4.75:1.

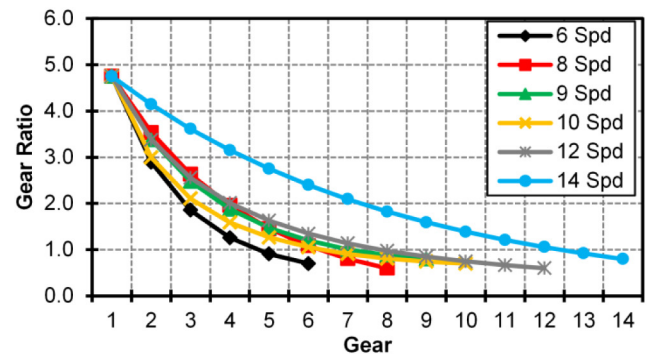


Figure 2. Gear ratios for 6, 8, 9, 10, 12 and 14 speed automatic transmissions with 4.75:1 launch gear ratio and various ratio progressions and top gear ratio.

It can be noted in Figure 2 that progressions, or step size of successive gear ratios, are not alike. A logarithmic ratio stepping progression is often the objective target for new transmission designs from a driving comfort perspective as mentioned by [12] and noted in most recent transmission designs, see [4, 5 and 11]. However, with forward gear counts continuing to increase it has not been established if other ratio stepping progressions are more ideal from a fuel consumption perspective. To determine the effect of ratio progression on fuel consumption three progressions were included in the L18 array. The progressions include a geometric, constant step size progression, a linearly decreasing step size progression and a logarithmically decreasing step size progression. As an example, Figure 3 shows the three ratio progressions used the 8 speed automatic transmissions simulated in the L18 array.

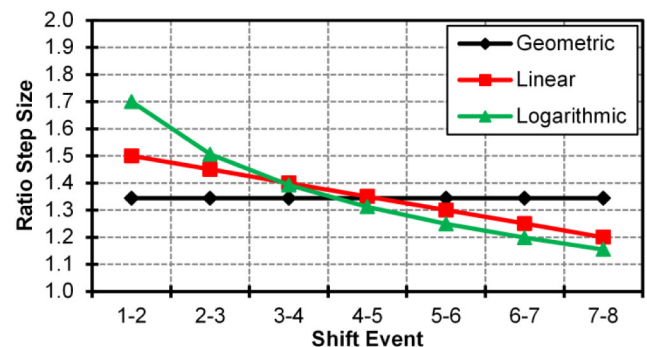


Figure 3. Geometric, linear and logarithmic ratio progressions applied to all transmissions of the L18 array, but shown in detail for 8 speed configuration only.

Launch and Top Gear Ratios

Overall ratio (OAR) spread is defined by the ratio of launch (1st) gear ratio and top gear ratio. Both of these parameters were included in the L18 array and varied at three levels each to determine their influence on fuel consumption. Table 2 summarizes the launch gear and top gear ratios selected and the corresponding OAR spreads. The gear ratios selected for this study span a typical range found in most current transmission designs.

Table 2. Launch gear ratios, top gear ratios and corresponding overall ratio spreads for automatic transmissions considered in L18 DFSS array

Top Gear Ratio	Launch Gear Ratio		
	4.25	4.75	5.25
0.60	7.08	7.92	8.75
0.70	6.07	6.79	7.50
0.80	5.31	5.94	6.56

Transmission Loss Mechanisms

Three major parasitic loss mechanisms exist within automatic transmissions. Two originate from the gearing and clutching systems while the third comes from the high pressure hydraulic pump required to provide charging pressure for the shifting system and torque converter as well as lubrication and cooling flow. All three of these loss mechanisms were included in the L18 array as transmission spinloss, pumploss and gear mesh efficiency.

Transmission spinloss for the various speed count transmissions were analytically derived from leading edge planetary automatic transmission designs and the methods described in [12 and 13]. The spinloss is an aggregate value for the transmission based upon input speed, operating line pressure, number of gears and oil viscosity. The number of gears determines the number of required clutch elements and the number of clutches unapplied for operation in a given gear state. An example of the transmission spinloss as a function of the number of transmission forward gears is provided in Figure 4, showing the averaged spinloss across all forward gears at a line pressure of 500 kPa for various input speeds. In general as the number of forward gears increases so too does the spinloss because of increased clutch count. As part of the L18 array, the losses for a particular transmission were scaled +/- 30% from the nominal calculated values to determine the relative influence on fuel consumption. A 30% deviation is estimated to comprehend the range typical of spinloss differences resulting from actual execution of an automatic transmission design.

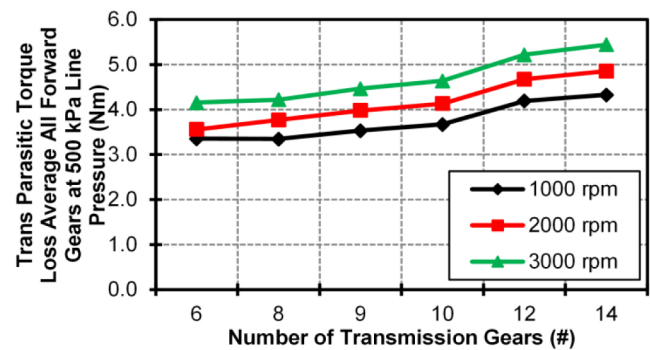


Figure 4. Transmission parasitic spinloss for various input speeds, averaged over all forward gears for a particular speed transmission at 500 kPa line pressure and 90 °C sump temperature.

Gear mesh efficiency for a planetary automatic transmission is the net efficiency of the total gear train from input to output and is multiplied by transmission input torque. Based upon leading edge three and four simple planetary gearset automatic transmission powerflows that encompass 6 through 14 speeds, estimates for gear mesh efficiency were established for this investigation. As an example of the mesh efficiencies used, Figure 5 shows the nominal mesh efficiency for an 8 speed transmission with a logarithmic ratio step size. To ascertain the relative importance of mesh efficiency on automatic transmission fuel consumption performance the nominal values by gear for all the transmission was varied -1 and -2% according to the L18 array.

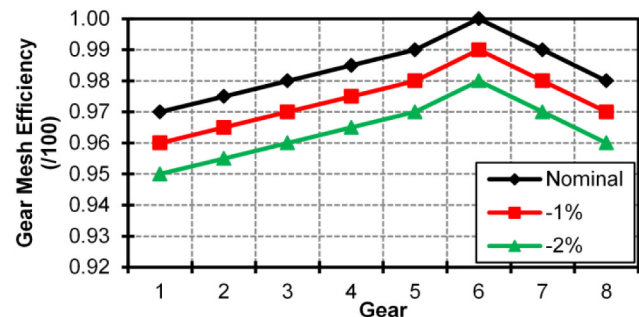


Figure 5. Nominal, -1% and -2% gear mesh efficiencies for an 8 speed transmission used in L18 DFSS array.

A single hydraulic pump technology was considered for all the transmission designs of the L18 array. The pump is binary in function, meaning there are two distinct regions of flow operation that yield the torque demands shown in Figure 6 to produce a given line pressure. Similar to transmission spinloss, pumploss was varied +/- 30% from the nominal values shown in Figure 6 to accommodate for variations in actual hardware execution and determine the relative influence of transmission pumploss on fuel consumption. It is assumed that the transmission pump will be driven at engine speed through some form of mechanization by the torque converter pump hub.

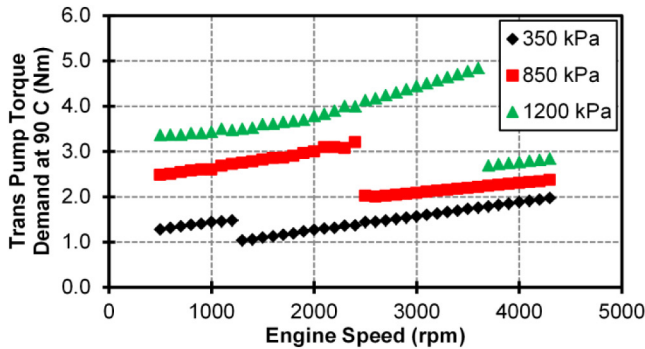


Figure 6. Binary transmission pumploss as a function of engine speed and line pressure demand at 90 °C.

L27 Inner Array - Automatic Transmission Design Parameters and Shift Pattern Constraints

The second DFSS study utilizes an L27 array design that includes thirteen parameters each at three levels. In this formulation, the effect of transmission design parameters were combined with shift pattern constraints and operating parameters. The goal was to determine relative performance impact of transmission hardware and shift point control. From the L18 study, 8, 9 and 10 speed transmissions with the characteristics as previously described were used. The shift pattern constraint parameters considered were minimum operating speed in gear for non-decelerating fuel cutoff (nonDFCO) and decelerating fuel cutoff (DFCO) gears, vehicle speed hysteresis between upshift and downshift lines, minimum operating gear ratio for DFCO, maximum engine torque scaling factor used to generate the shift pattern, the minimum time between upshifts and percent pedal hysteresis between upshift and downshift lines. All of these parameters provide boundaries and constraints on the shift patterns generated for the automatic transmissions of the DFSS inner array. A summary of the L27 parameters and their levels are contained in Table 3. It should be noted that parameter H has been split into two parameters due to its dependency on engine fueling status during deceleration (coast down) but are still coupled. The full layout of the L27 inner array with uncoded parameters can be found in Appendix A.

Table 3. Summary of automatic transmission hardware and shift pattern constraint parameters used for L27 inner array.

Parameter		Level		
A	Number of Gears	8	9	10
B	Ratio Progression	Geometric	Linear	Logarithmic
C	Top Gear Ratio	0.6	0.7	0.8
D	Launch Gear Ratio	4.25	4.75	5.25
E	Trans Spinloss	-30%	Nominal	+30%
F	Trans Pumploss	-30%	Nominal	+30%
G	Gear Mesh Efficiency	Nominal	-1%	-2%
H	* Min in Gear Speed nonDFCO	900	1000	1100
H	* Min in Gear Speed DFCO	1000	1200	1400
I	Shift Hysteresis	-50%	Nominal	+50%
J	min DFCO Gear	-1 Gear	~ 1.4 GR	+1 Gear
K	Eng Torque Scaling	100%	85%	70%
L	Time between PU's	1 sec	1.5 sec	2 sec
M	Pedal Hysteresis	-50%	Nominal	+50%

Shift Pattern Parameters and Constraints

The shift pattern parameters and constraints used in the L27 inner array are shown graphically in Figure 7 for further understanding. The parameter of minimum operating speed in gear is defined for both nonDFCO and DFCO conditions and is defined on a transmission input speed basis which will set vehicle speed at which a downshift will occur. Shift hysteresis defines the vehicle speed spacing between upshift and downshift during light pedal. Pedal hysteresis defines the upshift - downshift line spacing with respect to pedal position during higher pedal tip-in, tip-out conditions. Both of these constraints define shift busyness of the transmission. Scaling of engine torque capability when developing a shift pattern will result in pushing out of upshift lines and create downshift that are more available as indicated by the dashed lines in Figure 7. This calibration strategy builds torque reserve within the shift pattern. The minimum operating gear state in which DFCO is used (not shown in Figure 7) is defined as the gear state that has a numerical ratio closest to a value of 1.4:1. Minimum time between upshift constraint becomes an important parameter when the number of forward gear states increases to the point that upshifts become stacked and add to shift busyness. Adding a time constraint between upshifts will generally degrade fuel consumption of high gear count transmissions as upshifts are pushed out but reduces perceived shift busyness.

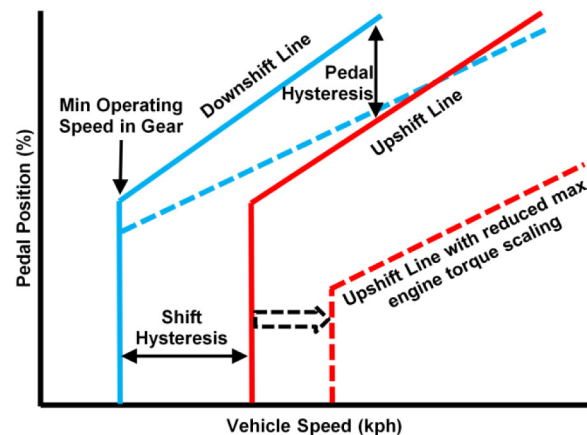


Figure 7. Definition of automatic transmission shift pattern constraints for L27 DFSS study.

Outer Array - External Noise Factors

There are numerous factors external to a particular automatic transmission design that will influence its performance in terms of fuel consumption. In DFSS terminology, these factors are referred to as noises that cause variation from ideal performance. For this investigation, the external noises that affect the overall performance of the powertrain - vehicle system while investigating the influence of transmission parameters are the defining characteristics of the vehicle, the engine pairing, the final drive ratio selected to meet driving objectives and the emissions test schedule used to certify and report fuel consumption. Two vehicles were selected to analyze in the DFSS outer array, one a FWD sedan and one a RWD truck, as these are typically high volume vehicle applications. Each vehicle was combined with two engines of nearly equal peak torque, three final drive ratios and simulated over three emissions test schedules. The noises for the outer array are summarized in Table 4.

Table 4. Summary of outer noise array parameters combined with either L18 or L27 inner array.

Noise		Level			
N1	Vehicle	FWD Sedan		RWD Truck	
N2	Engine	FWD Eng 1	FWD Eng 2	RWD Eng 1	RWD Eng 2
N3	Test Schedule	FTP	US06	WLTP	
N4	Final Drive Ratio	FWD	2.9	3.2	3.5
		RWD	3.1	3.4	3.7

Vehicles

Both FWD and RWD powertrain configurations were considered in this investigation as a FWD sedan and a RWD truck. A 1760 kg sedan with a road load power requirement of 12.8 kW at 100 kph represents the FWD application while a 2380 kg truck with a road load power requirement of 22.1 kW at 100 kph represents the RWD application. Both of these vehicles are current production in which measured road load characteristics were available to include in the analysis.

Engines

Each of the FWD and RWD vehicles were each combined with two engines. The engines for each powertrain orientation were selected based upon having as close as possible peak torque characteristics so that acceleration performance could be considered approximately equivalent.

Figure 8 contains the maximum torque across engine speed range and minimum bound of brake specific fuel consumption (BSFC) as a function of brake mean effective pressure (BMEP) for the FWD vehicle. FWD Eng 2 has a downsizing ratio of 36% relative to FWD Eng 1. FWD Eng 2 is noted to have higher torque capability in the low speed range as well as a wider BMEP range in comparison to FWD Eng1. FWD Eng 1 has lower BSFC value throughout most of the range of BMEP.

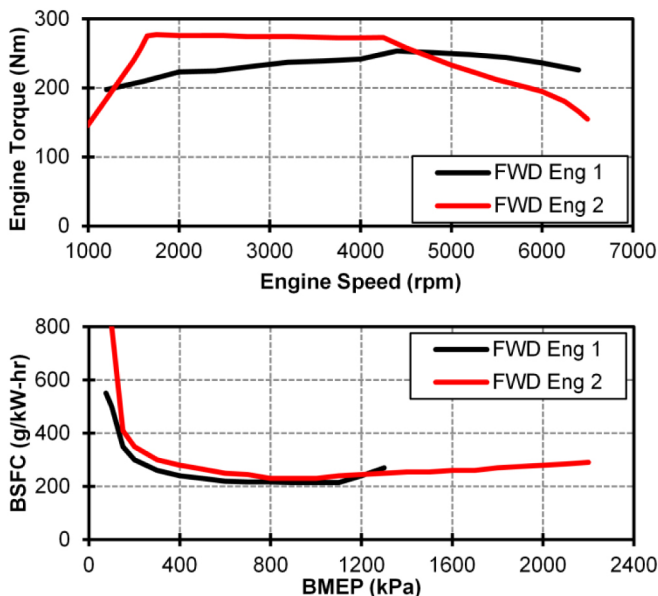


Figure 8. Maximum torque and minimum BSFC vs. BMEP for FWD sedan engines used in outer noise array.

The two engines selected as part of the noise array for the RWD truck vehicle are shown in Figure 9. RWD Eng 1 has the capability to deactivate half of the operating cylinders to reduce fuel consumption, a design and operating characteristic described in more detail by [14]. RWD Eng 2 has a downsizing ratio of 32% with respect to RWD Eng 1 and does not have cylinder deactivation. When operating in full cylinder mode both RWD engines have nearly equivalent BSFC at equivalent BMEP. The limited BMEP operating range for half cylinder mode for RWD Eng 1 is defined in Figure 9.

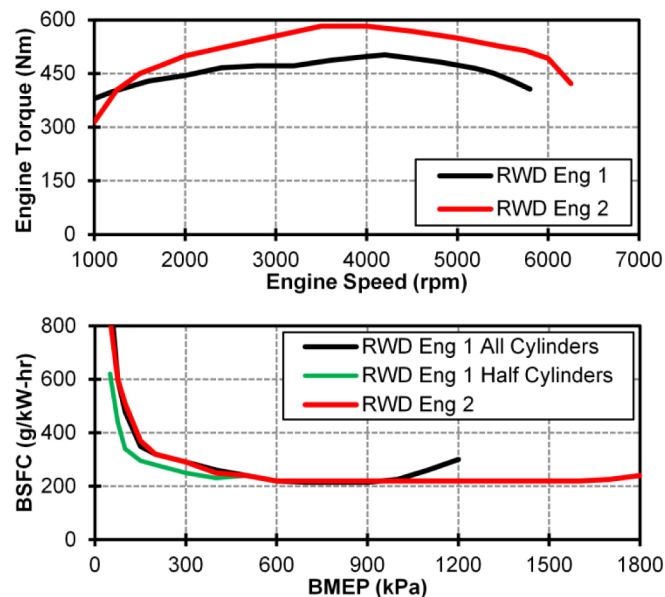


Figure 9. Maximum torque and minimum BSFC vs. BMEP for RWD truck engines used in outer noise array.

Test Schedules

Three regulated emissions test schedules were used as part of the DFSS outer noise array. The test schedules included are the EPA's Federal Test Procedure (FTP) with both city and highway components, EPA's US06 aggressive highway schedule and the United Nations Economic Commission for Europe (UNECE) Worldwide harmonized Light vehicles Test Procedure (WLTP) for class 3 vehicles. These three schedules were chosen for their variety of vehicle driving conditions and regional testing requirements. The mean performance of the three test schedules should provide a fair representation of the relative fuel consumption performance of a wide range of hypothetical transmission designs over a wide range of vehicle maneuvers. Figure 10 contains the vehicle speed profiles verse time for the three test schedules. For all test schedules, the effect of transmission thermal transient warmup was omitted by considering the transmission oil sump temperature to be starting at a hot condition of 90 °C.

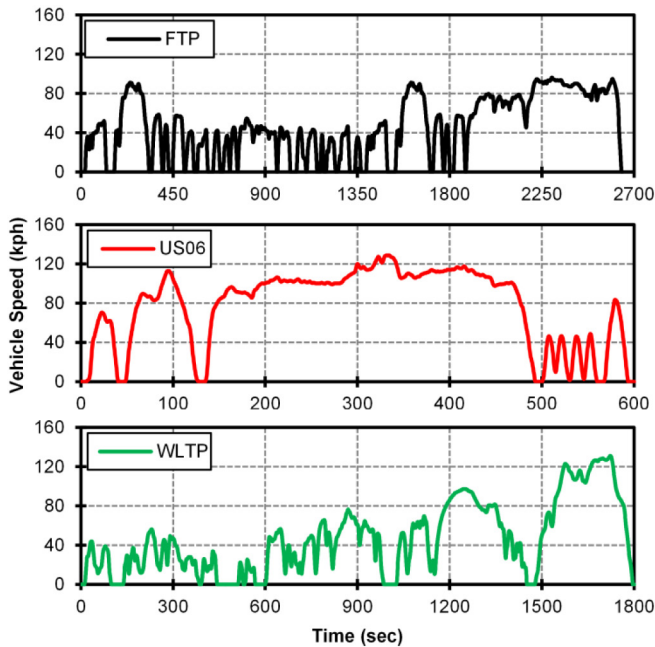


Figure 10. Vehicle speed vs. time traces for FTP, US06 and WLTP test schedules used in outer noise array.

Final Drives

For this investigation three final drive ratios (FDR) were used with both FWD and RWD configurations and were selected to span the range commonly available to achieve a desired balance of acceleration and fuel consumption performance. Skewed towards reduced fuel consumption, a 2.9 and 3.1 FDR were used for FWD and RWD, respectively. A 3.5 FDR for the FWD and a 3.7 FDR for the RWD were used to balance performance towards acceleration. Final drive ratios of 3.2 and 3.4 for FWD and RWD, respectively, were used as a balance FDR for acceleration and fuel consumption. A more thorough analysis might include the full range of FDRs possible for a particular transmission and vehicle application. It should be noted that the FDRs used in the study are for illustrative purposes only and are not meant to represent actual FDRs that can be manufactured.

Energy Analysis Method

A first principles, energy based analysis technique was utilized in this investigation to simulate the fuel consumption performance of the powertrain - vehicle systems for both the L18 and L27 DFSS studies. The modeling technique and key assumptions around the powertrain - vehicle system follows closely the approach described by [6]. The MATLAB®/ Simulink® based model includes all the relevant dynamics and powertrain controls features common to conventional powertrain - vehicle systems that contribute to the determination of performance and fuel consumption as depicted in Figure 11. All sources of energy input and energy flows are detailed by measured or empirically derived data in lookup tables as a function of speed, load, temperature, operating pressure, and/or gear state. The model solver is based upon a tunable observer following the predefined vehicle

velocity schedules contained in Figure 10. In general, this type of modeling approach shows good correlation with physical test results; see [6 and 12] for details. Since all the automatic transmissions in the L18 and L27 arrays are hypothetical designs, there is no hardware test data available for correlation with the modeling results.

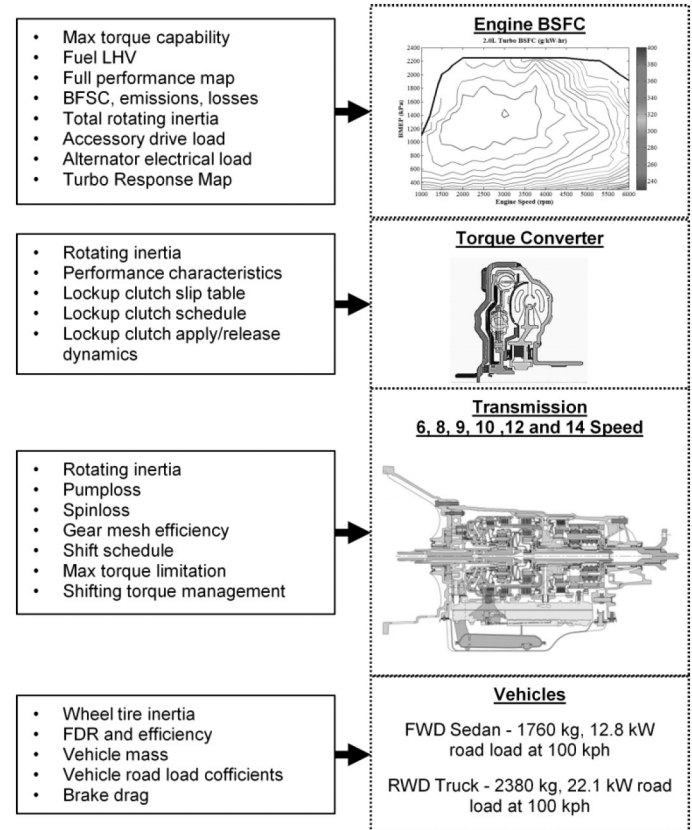


Figure 11. Summary of inputs to energy analysis method used to conduct L18 and L27 array DFSS studies.

Shift Pattern Generation

For each unique powertrain - vehicle - FDR combination a unique shift pattern was generated using an optimization algorithm. All the relevant parameters of the powertrain and vehicle are taken into account to examine best operating point while still meeting road load requirements. A cost function based upon minimizing the ratio of engine fuel rate to axle power,

$$\Psi = \min \left(\frac{\dot{m}_{fuel}}{P_{axle}} \right) \quad (1)$$

is calculated at every possible pedal position and vehicle speed. The gear state corresponding to the minimum value of Eq (1) is combined with the shift pattern constraints and parameters described previously to define upshift and downshift lines. This general procedure follows that outlined by [15] and results in a very plausible shift pattern so long as reasonable shift pattern constraints are employed that correlate