

Internal Combustion Engine - Automatic Transmission Matching for Next Generation Power Transfer Technology Development in Automotive Applications

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ABSTRACT

Development of the next generation internal combustion engines and automatic transmissions for automotive applications is a mandatory powertrain engineering activity required now and in the coming years to meet forthcoming global emissions regulations. This paper details a preliminary investigation into possible synergies for fuel consumption reduction considering emerging automotive technologies integrated into the next generation combustion engine and automatic transmission architectures. A range of hypothetical gasoline engines were created and paired with a generalized set of step gear automatic transmissions designed to meet the performance requirements of high volume longitudinal full size truck application. These designs were then run through a design of experiments orthogonal array for prediction of fuel consumption on the WLTP test schedule and stand still acceleration to 100 kph. Results from the design of experiments agrees with previous investigations with regards to required transmission gearing selection even with profoundly different engine brake specific fuel consumption maps. New automatic transmission concepts were then developed with the objective to alter the paradigm for step gear automatic transmissions. A number of unique automatic transmission concepts are discussed at length for longitudinal applications, including architecture and functionality, that match the performance attributes of the next generation gasoline engines. These designs represent a reduction in fuel consumption from current 6 speed planetary technology at a minimum of 2% while maintaining equivalent or better acceleration characteristics.

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INTRODUCTION

The current trend in step gear automatic transmissions is increasing number of forward gear ratios beyond 6, stabilizing for the moment at 8 to 10 in either transverse or longitudinal applications, [1, 2 and 3]. Simultaneously, technologies such as high efficiency gears, pumps, low spinloss bearings, seals and clutches, all coupled with aggressive calibration of shift patterns and early torque converter clutch lockup are being implemented on automatic transmissions to reduce losses and improve overall operational efficiency. Previous research on conventional powertrain matching optimal number of forward gear ratios and transmission technologies have largely only looked at current or near horizon engine designs see [4, 5 and 6]. A recent study, [7], have looked at over the horizon engine designs, integrating new technologies for drastically improved performance and what automatic transmissions pair best for fuel consumption on a given regulatory test schedule. In general, the authors have countered that the current trajectory of number of forward fixed gear ratios is unnecessary given the increased torque capability at low engine speeds and wider regions of minimum brake specific fuel consumption, BSFC, fewer forward gear ratios are required, potentially as few as four, see [7]. This study also proposed a new automatic transmission design, however, augmented with some form of parallel electrification to supplement the internal combustion

engine. The aim of this investigation is to examine the validity of these claims through a detailed analysis approach considering engines with widely varying performance in a given vehicle application and propose alternative step gear automatic transmission concepts.

This investigation has two primary objectives, carried out using analytical methods and focused exclusively on conventional automotive powertrain machinery. The first objective was to determine design parameters for the next generation step gear automatic transmissions that best match the operating characteristics of current and anticipated future internal combustion engine designs based upon industry mega trends. Internal combustion engines will continue to increase torque output while reducing fuel consumption and emissions through mechanical design, controls and added features such as those mentioned by [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. These future internal combustion engines will have an increase in mean brake torque at lower engine speeds while also achieving lower BSFC over a wider range of engine speeds and brake mean effective pressures, BMEP. Figure 1 graphically highlights this trend in engine design and calibration, largely achieved through changes to valvetrain technology, combustion mechanism, friction reduction, downsizing, turbocharging and direct injection, see [8, 9, 10, 11, 12, 13] for details.

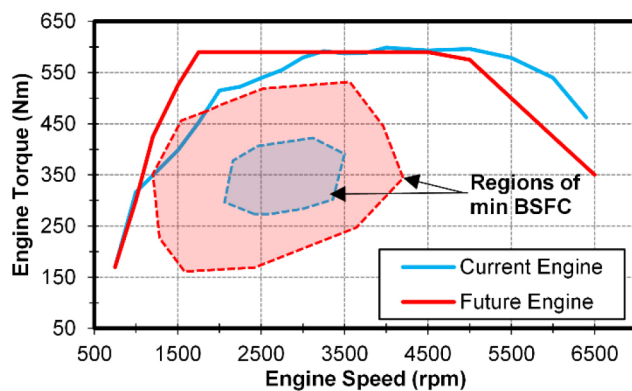


Figure 1. Engine speed versus torque plot representing future trend in internal combustion engine design, minimum BSFC regions shown for each engine.

The second objective of this investigation is to present alternative step gear automatic transmission powerflow architectures that will synergize with previous research on conventional powertrain matching as well as the results contained in this investigation. The proposed transmission concepts are intended to match both current and future engine performance and vehicle applications. In general, the step gear automatic transmission concepts presented contain multiple input clutches, are layshaft versus planetary architecture principally to reduce rotating inertia, operating losses, increase acceleration performance capability and afford greater flexibility in individual forward gear ratio selection.

MATCHING ENGINE AND STEP GEAR AUTOMATIC TRANSMISSION DESIGNS

Conventional powertrain matching of internal combustion engines and step gear automatic transmissions has been a perennial activity amongst powertrain engineers and researchers, [1, 2, 3, 4, 5, 6, 7]. Recent analytical studies by [4, 5 and 6] highlight new technology integration combined with statistical approaches to select the optimal transmission design parameters for best fuel consumption. This investigation will continue this approach, using a fractional factorial design to assess quickly the influence of key parameters using an orthogonal array containing seven design parameters for step gear automatic transmissions arranged into 18 unique combinations. Each of the 18 transmission variants were then simulated with 8 different engines and 4 final drive axle ratios on a single vehicle application. The particulars of the analysis will be described in the subsequent sections, detailing the vehicle, engines, transmissions, test schedule, shift pattern creation and all other key assumptions. It is worth remarking that the parameter values defining the light duty, full size truck and all automatic transmissions are hypothetical paper designs and do not directly represent current or future product intent. The engines are a combination of existing designs and conjectural future engines extrapolated from the existing designs.

Vehicle

For this investigation a light duty, full size truck was considered as the principal candidate for analysis of future conventional powertrain matching. Such a vehicle was considered, as it is critical in the North American region market on a volume and per vehicle profit basis. It also represents the vehicle segment with the greatest opportunity to reduce greenhouse gas, GHG, emissions and fuel consumption on an absolute versus relative perspective. The vehicle is defined with a mass of 2200 kg, which assumes a significant amount of lightweighting from current generation light duty, full size trucks that are in the range of 2500 to 2600 kg. Road load power is expressed through a curve-fitting coast down coefficients with values of 150, 6.5 and 0.52 with units of N, N-s/m and N-s²/m, respectively. The road load power as a function of vehicle speed on a zero grade is shown in Figure 2, requiring roughly 20 kW of power at 100 kph.

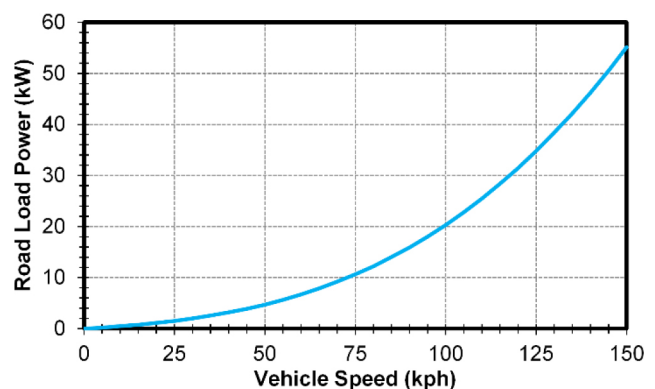


Figure 2. 2200 kg light duty, full-size, truck road load power as a function of vehicle speed, 0% grade.

Current and Future Engines

A survey across multiple original equipment manufacturers of this vehicle segment shows a wide array of internal combustion engines offered, as the prime source of propulsion. Engines range from gasoline to diesel, naturally aspirated to turbocharged, with the latest generation variable valve timing, direct fuel injection and potentially cylinder deactivation. For this investigation, three engine variants with characteristics covering the width of applications in the current market place were selected and included in the analysis array. A fourth engine was created from an existing base engine data set to represent a future engine design with a modified maximum brake torque envelop, namely, higher torque output below 2000 rpm achieved through a specific turbocharging strategy, see [10] for example. Engine fuel consumption will most likely continue to decrease with future engine designs as engineering and technologies progress. To examine the influence improved fuel consumption will have on step gear automatic transmission gearing selection the BSFC maps for all four engines were scaled in certain speed-torque regions. The approximate scaling is based upon engine technologies and strategies mentioned in the literature, [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18], for example. These hypothetical engines then became

derivatives of their base engines with the same specific torque output, but will lower and wider BSFC contours in the core operating region of nearly all regulatory test schedules. To facilitate direct comparison of optimal transmission design parameter selection, the maximum brake torque output of all the engines was held fixed while fuel consumption was scaled. The details of these engines and the fuel map scaling is detailed in the next sections.

Large Displacement V8 Gasoline with Cylinder Deactivation

The large displacement gasoline V8 engine is one of the more common prime movers found in the light duty, full size truck segment and is included in this investigation. The particular engine has cylinder deactivation, V8 to V4, to reduce fuel consumption. Peak torque output is slightly above 500 Nm as noted in Figure 3. Baseline engine performance is noted in the left plot of Figure 3 and the reduced fuel consumption map is shown on the right. Minimum fuel consumption is around 245 g/kW-hr for the baseline engine, occurring between 1000 and 4000 rpm, and 225 to 400 Nm. The minimum BSFC island was increased in size and depth, spanning the same speed range, but opened to 200 Nm, dropping to a specific consumption of 200 g/kW-hr.

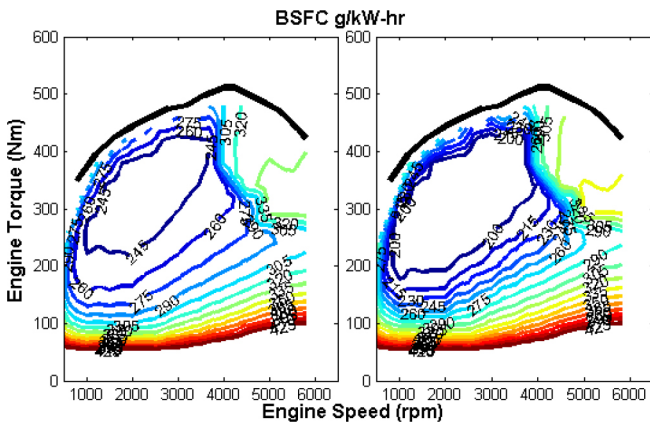


Figure 3. Gasoline V8 engine maximum brake torque and BSFC contour maps for baseline and reduced fuel consumption engines.

Downsized Turbocharged V6 Gasoline

Another engine entry in the light duty truck market are downsized, turbocharged, abbreviated DSB, direct injected V6 gasoline engines, which were also included in this study. The performance data for the baseline and reduced BSFC island variants of this engine are included in Figure 4. Maximum engine torque is at 600 Nm at roughly 3000 to 5000 rpm and a minimum BSFC of 230 g/kW-hr at a roughly 2750 rpm and 350 Nm. The hypothetical, reduced fuel consumption engine variant greatly expands the minimum BSFC island at 200 g/kW-hr to occur between speeds of 1200 to 3700 rpm and torques of 180 Nm upwards of 450 Nm. The reduced BSFC engine variant represents an approximate reduction of 13% in fuel consumption.

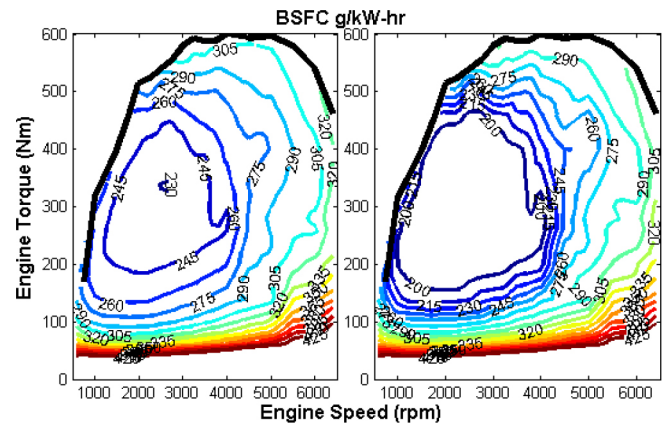


Figure 4. Downsized boosted V6 gasoline engine maximum brake torque and BSFC contour maps for baseline and reduced fuel consumption variants.

Turbocharged Diesel V6

A new engine entry into the light duty truck market is the turbocharged diesel V6. Utilization of such an engine will likely be expanded in this particular vehicle segment to improve emissions sufficiency and performance capabilities of the vehicle. As noted in Figure 5, engine torque output peaks at 550 Nm across a narrow speed range with minimum BSFC occurring throughout the typical driving range above 250 Nm. A reduction in fuel consumption of approximately 7% was assumed with the reduced BSFC variant achieved largely through combustion efficiency improvements found with methods reported by [9 and 10].

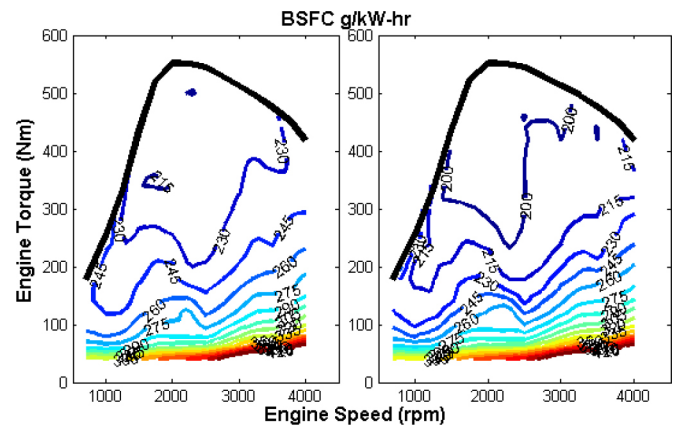


Figure 5. Downsized boosted diesel engine maximum brake torque and BSFC contour maps for baseline and reduced fuel consumption variants.

Future Downsized Turbocharged V6 Gasoline

It is anticipated that the megatrends in DSB gasoline engines will continue in future automotive powertrain applications with continued effort to increase torque capability and reduce fuel consumption. To capture this trend in engine design, a hypothetical engine was created to include in the analysis matrix. The particular engine presented here was an extrapolation of engine presented in Figure 4, with torque output increased in the 1200 to 3000 rpm range as noted in Figure 6. Similarly, BSFC was scaled in certain operating ranges to expand the

minimum island to be highly aggressive. This particular engine represents the best-case scenario for engine performance to influence transmission gearing selection for potentially showing if any direct correlation exists to enable a reduction in the number of fixed gear ratios.

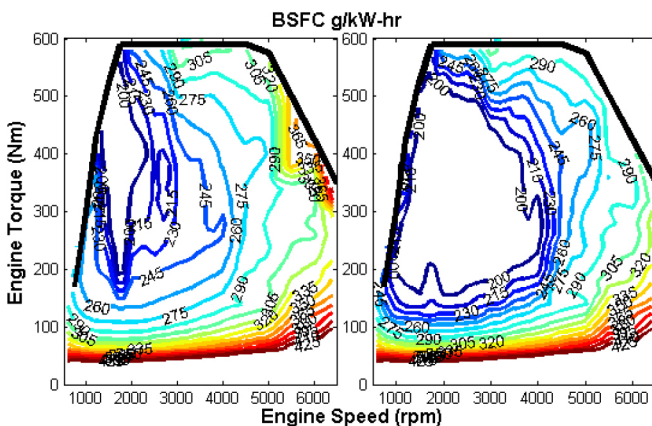


Figure 6. Hypothetical future downsized turbocharged V6 gasoline engine maximum brake torque and BSFC contour for baseline and reduced consumption variants.

Transmission Design Parameter Fractional Factorial Design - L18 Orthogonal Array

The design parameters for step gear automatic transmissions and shift pattern constraints incorporated into an L18 orthogonal array for analyzing the optimal matching of engine and transmission for performance are explained in the proceeding four sections.

Transmission Design Parameters

Table 1 contains the transmission parameters in the L18 orthogonal array, which includes number of fixed gear ratios, ratio progression, top gear and launch gear ratios, scaling factor for transmission spinloss, gear architecture and fundamental shift pattern constraints. These parameters were considered as they define the foundation of the step gear automatic for engine matching as well as determine overall performance potential. Scaling the transmission spinloss was included to encompass the variation that might be realized in actual parasitic losses that are highly dependent on powerflow selection, transmission layout and gear architecture. Gear architecture is included as a separate parameter, namely to differential spinloss from gear mesh efficiency as there are distinctly different values between planetary and layshaft transmission designs. A third option, layshaft with winding path, is a particular case of a layshaft transmission design that achieves unique gear ratios through multiple meshes of parallel axis gears, sometimes incorporating multiple countershafts. Such an architecture can increase the availability of fixed gear ratios while reducing the number of rows of gear pairs, but at the sacrifice of mesh efficiency. Appendix A of the paper contains the exact L18 orthogonal array layout and allocates each parameter into a unique transmission design and shift pattern specification, see Table A1 for more details.

Table 1. Step gear automatic transmission parameters included in the L18 orthogonal array.

Parameter	Level					
Number of Gears	7	8	9	10	11	12
Ratio Progression	Geometric		Linear		Logarithmic	
Top Gear Ratio	0.55	0.60	0.65			
Launch Gear Ratio	4.50	5.00	5.50			
Spinloss Scaling	-30%	Nom	+30%			
Gear Architecture	Planetary		Layshaft		Layshaft w/Winding Path	
Shift Pattern Constraints	1	2	3			

The intermediate gear ratios for all the transmissions were determined using the same methodology described in [6] to achieve the ratio progressions defined as geometric, equally spaced ratio step size, linear, linearly decreasing step size from first step to last step and logarithmically decreasing ratio step sizes. The overall ratio spreads, OAR, that were produced from the combinations of launch and top gear ratios are summarized in Table 2, ranging from 6.92 to 10.00. This range covers existing step gear designs but goes beyond to consider extremely wide ratio spreads not currently available in automotive applications.

Table 2. Overall ratio spreads for transmission in the L18 orthogonal array.

	Launch Gear Ratio		
Top Gear Ratio	4.50	5.00	5.50
0.55	8.18	9.09	10.00
0.60	7.50	8.33	9.17
0.65	6.92	7.69	8.46

Transmission Losses

As reported by a number of case studies on automatic transmission design, such as [3, 4, 5, 6 and 19, 20, 21], parasitic losses can significantly influence fuel consumption. A uniform approach to developing spinloss values was utilized such that it could more readily be understood what influence it has on transmission engineering and minimize the opportunity for it to obscure the objectives of the study. For each of the unique transmission combinations created from Table 1 and Table A1 in Appendix A, a spinloss table was created as a function of input speed, input torque and gear state. The general form of the spinloss, which includes losses at open clutch(es), bearings and seals, is shown in Figure 7 for a 10 speed transmission at line pressures of 500 and 1200 kPa and input speeds between 1000 and 2500 kPa. The spinloss calculations were developed by looking at existing planetary and layshaft transmission designs at a nominal warm operating temperature.

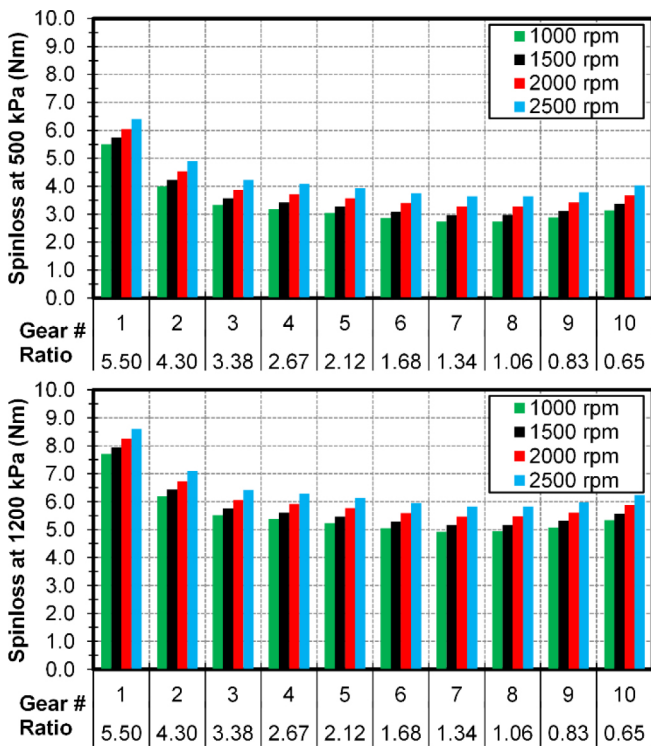


Figure 7. Example transmission spinloss as a function of input speed, line pressure and gear state, shown for line pressures of 500 and 1200 kPa.

The spinloss dependency on line pressure originates from input torque, which dictates lube pressure and flow to the transmission. For all transmissions, line pressure, P_{line} , was a fixed relationship for all gear states given by,

$$P_{line} = 2.25(T_{input}) + 200 \quad (1),$$

which is input torque, T_{input} , times a gain of 2.25 plus an offset of 200 kPa. Maximum line pressure was set at 2100 kPa, corresponding to a maximum input torque of 845 Nm, which is typical of an automatic transmission to be matched to the output of the engines considered for this investigation. As part of the orthogonal array parameters, spinloss was scaled +/- 30% or held at the nominal values. For layshaft transmissions, the nominal values were reduced by 15% to reflect the lower losses associated with this type of architecture, namely splash lubrication and minimal open clutches.

Separate from spinloss is the parasitic losses associated with a high pressure hydraulic pump to actuate clutches and shift forks as well as provide lube flow. Pump losses were included as a separate input to the analysis, being a function of input speed and line pressure requirement. The same pump design was applied to all transmission in the orthogonal array, featuring binary action to reduce losses. The

value of torque consumed to operate the transmission pump ranged between 1.25 to 6 Nm depending on operating conditions and mode of the pump.

A third parasitic loss mechanism included is gear mesh efficiency, or torque loss due to friction at the mesh interface for gear teeth. For planetary transmissions, the values were a function of gear ratio, having lowest values in the 97% range at launch ratios, peaking at 100% at 1:1 ratio and dropping back to 98 to 99% at top gear ratio. A gear mesh efficiency of 98% was applied to all gear ratios for layshaft transmission architectures with the exception of those considered to have winding path gear ratios. For the latter type of layshaft one third of the fixed gear states were considered to have winding paths, primarily in the intermediate gear ratios and were assigned a value of 96% to account for the additional meshes participating in torque transfer.

The last energy loss mechanism included relates to transmission shift dynamics. During upshift or downshift events, energy loss due to slipping clutches and engine torque reductions during upshift events was included as part of the powertrain model. As discussed in [22], this is a nontrivial loss of energy and as the number of forward gears increases, so too does the number of shifts performed on a given test schedule. As will be discussed later, this aspect of automatic transmission operation can hinder the potential benefit of increasing the number of gear states as more energy is consumed by the transmission through higher frequency of shift events if not compensated by achieving engine operation that significantly reduces fuel consumption.

Launch Device

All transmissions in the orthogonal array were considered to have a torque converter and lockup clutch as the launch device irrespective of the gear architecture, e.g. planetary vs. layshaft, which would typically see wet clutches. This was done to simplify the analysis and eliminate the energy utilization benefits of various launch device types. It also facilitates the comparison solely on the effect of the fundamental transmission design versus the combination of transmission and launch device. Two torque converter K-factors were used to match the performance of the four engines analyzed. A low K-factor unit for the large displacement V8 gasoline engine was utilized, while a higher K-factor unit for the smaller turbocharged engines to enable more rapid rises in engine speed on launch and lockup clutch release events was considered. In addition, the torque converter is used only at launch, with the lockup clutch applied right at the 1-2 upshift and fully locked through all power on operation and for non-fueled coast down conditions. The torque converter clutch is released immediately following engine refueling during vehicle coast down. This attribute of operating strategy further marginalizes the choice of a torque converter for all transmission simulations.

Shift Pattern

The assumption of shift pattern constraints and transmission operating point can also be a significant contributor to overall performance and fuel consumption. Thus, it was included as one parameter in the L18 orthogonal array. The goal was to demonstrate overall effect on fuel consumption relative to design parameters and if the relative influence varies greatly between drastically different engines. A thorough discussion on all the shift pattern constraints and assumptions can be rather lengthy, so the major assumptions and strategies employed in this investigation are summarized in [Table 3](#) as well as [Table A2](#) in [Appendix A](#).

Table 3. Major shift pattern constraints and operating strategy assumed for this investigation.

Constraint	Description
Minimum operating speed for gears using coastdown fuel cutoff	Either 1200 rpm or 1100 rpm, see Table A1 for details
Minimum operating speed for gears not using coastdown fuel cutoff	800 to 900 or idle speed plus 100 rpm, see Table A1 for details
Minimum gear ratio before engine refuel on coastdown	For non-aggressive pattern gear ratio closest to 1.5:1, for aggressive shift pattern between 3:1 and 2.5:1
Upshift-downshift hysteresis	For non-aggressive pattern 3 to 4 kph, for aggressive shift pattern 1.5 kph
Torque converter lockup clutch apply	Applied right at 1-2 upshift, fully locked for all higher gears for power on condition
Torque converter lockup clutch release	Released on coastdown before downshift in which engine is refueled
Upshift shift times	0.65 seconds for 7 speeds, decreasing monotonically to 0.35 seconds for 12 speeds
Downshift shift times	0.50 seconds for 7 speeds, decreasing monotonically to 0.35 seconds for 12 speeds

The exact procedure for creating the shift pattern has previously been detailed at length in [5 and 6], which roughly approximates the approaches reported by [23 and 24]. The foundation of finding the optimal gear state is predicated on a minimum search function on the metric of mass flow rate of fuel at the engine normalized by power delivered at the axle. This method comprehends the net efficiency of the entire powertrain and driveline in selection of the optimal gear state for minimum fuel consumption. Additionally, system constraints are imposed upon this raw shift map to include the requirement to meet road load power as well as typical hardware limitations such as pump limits, drivetrain resonances, vehicle NVH and drive quality constraints. A typical shift pattern for a particular 10 speed transmission studied in the L18 investigation is shown in [Figure 8](#).

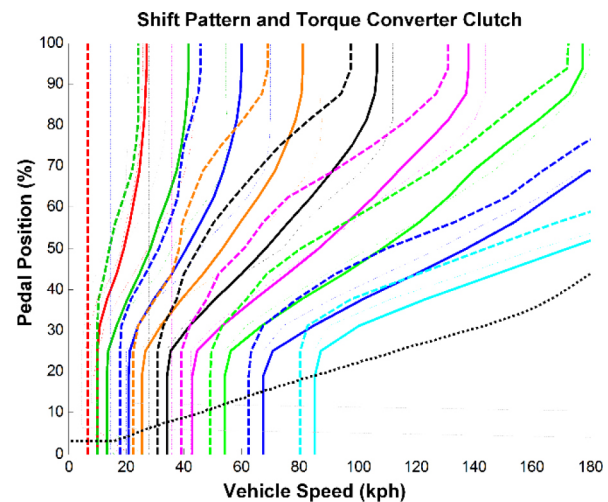


Figure 8. Shift pattern created for 10 speed with the gasoline V8 engine and 3.42 axle ratio following the outlined specific optimal gear search and pattern constraint methodology.

Final Drive Axle Ratios

Four final drive axle ratios were added to the analysis matrix for each engine and transmission combination. The exact final drive ratios used in the analysis are provided in [Table 4](#). An axle efficiency of 96% percent was assumed across all operating torques and speeds.

Table 4. Final drive axle ratios used in analysis matrix combined with each engine - transmission combination.

Axle Ratio 1	Axle Ratio 2	Axle Ratio 3	Axle Ratio 4
3.08	3.23	3.42	3.73

Test Schedules

The Worldwide Light Duty Test Procedure, WLTP, see [Figure 9](#), was the single regulatory test schedule prescribed for this study. It was selected as it nearly equivalently approximates the fuel consumption performance and operating points realized through combining the Federal Test Procedure, FTP, and US06 test schedules without having to simulate both and calculate a composite fuel consumption. All simulation runs were made with the assumption of a warmed up and constant operating temperature powertrain at 90 C.

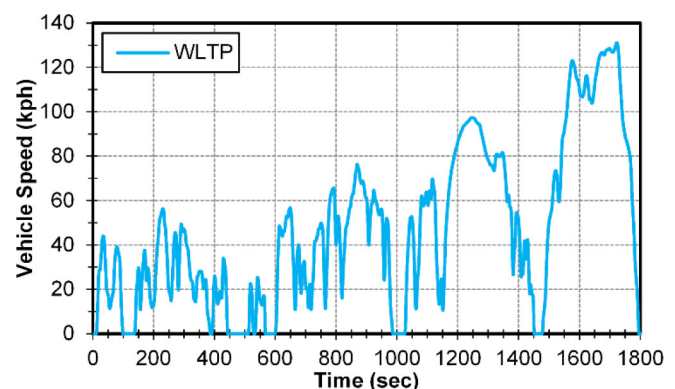


Figure 9. Vehicle speed versus time for the Worldwide Light Duty Test Procedure (WLTP) test schedule.  **Documents**
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