Proceedings of the American Control Conference
Anchorage, AK May 8-10, 2002

Torque Fill-In for an Automated Shift Manual Transmission in a Parallel Hybrid Electric Vehicle[1]

R. C. Baraszu and S. R. Cikanek
Ford Research Laboratory
Ford Motor Company
Dearborn, MI 48121-1170

ABSTRACT

An automated shift manual transmission (ASM) is utilized in a post-transmission parallel hybrid electric vehicle to take advantage of its high efficiency and lower cost compared to that of a fully automatic transmission with torque converter. However, a disadvantage of the ASM transmission is that torque to the drive wheels is disrupted during gear shifts when the clutch is disengaged from the engine, resulting in degraded shift quality over an automatic transmission/torque converter combination. In the hybrid configuration presented here, an electric motor is utilized to provide torque directly to the drive wheels during gear upshifts when the engine is disengaged from the transmission. This torque applied during the shift is referred to as fill-in torque and, if properly applied, can emulate the continuous torque provided by the automatic transmission with torque converter. Effectively, the shift quality of an ASM transmission can be made to approach that of a fully automatic one via proper control of the fill-in torque and engine clutch slip. The amount of motor torque applied and the length of time it is applied are optimized by minimizing an objective metric of transmission shift quality. This paper presents such a control scheme, parameter optimization process, simulation results, and vehicle data that validates the simulation.

1. INTRODUCTION

The automobile is an integration of many devices interconnected in a complex system. A conventional vehicle powertrain consists of a powerplant, such as a diesel or spark-ignited internal combustion (IC) engine, transmission, and driveline which includes a differential, axle system, and drive wheels. Many accessories are also connected to the powerplant such as a starter motor/alternator, low voltage electrical system, power steering system, water pump, power brakes, and air conditioning. These electrical, mechanical, chemical, and thermodynamic devices comprise a nonlinear, dynamic system which, ideally, meets or exceeds customer expectations for performance, including acceleration, braking, maneuverability, and comfort, while minimizing the impact on the environment.

[1] The hybrid vehicle research is part of DOE's Hybrid Propulsion Systems Development Program being conducted under a cost-shared subcontract funded equally by Ford and DOE through the Midwest Research Institute that manages and operates DOE's National Renewable Energy Laboratory in Golden, CO.

An Electric Vehicle (EV) powertrain consists of a traction motor connected to the drive wheels through a differential. A high voltage traction battery provides power to the motor. One limitation of the EV architecture is the necessity to use an external means of charging the battery. This is especially troublesome since such means may not always be easily accessible to the driver and generally require several hours to fully recharge a depleted battery. Other drawbacks include limited driving range (typically 100 miles per charge) and performance issues in extreme temperatures and under high loads.

Combining an EV system with conventional powertrain components results in a Hybrid Electric Vehicle [1]. A Parallel Hybrid Electric Vehicle (PHEV) consists of an electric motor and a conventional powertrain system combined such that tractive power can be delivered to the wheels by each device separately or by both devices in parallel. No external charging means (such as plugging in to an electric outlet) is required as the IC engine together with regenerative braking can keep the battery sufficiently charged. With a hybrid electric, charging the battery is now as easy as filling the gas tank!

Hybrid electric vehicles are motivated by the limitations of batteries contained in the EV and are capable of significantly improving the range and performance. Adding an auxiliary powerplant, such as an IC engine/alternator combination, along with an EV powertrain can potentially extend the vehicle performance envelope and fuel economy, while reducing the effect of emissions over a conventional powertrain alone.

The PHEV powertrain depicted in Figure 1 is synthesized using a conventional IC engine powerplant and starter/alternator combination connected via a servo-actuated dry clutch to an ASM transmission [2, 3]. The transmission output shaft is connected to one side of a 4x4 differential and then to two halfshafts and drive wheels. An ac induction traction motor is attached via a dry clutch to the other side of the differential in such a way that it can provide drive torque to the halfshafts independently of, or in combination with, the IC engine. The motor is sized (55 kW, 190 Nm) to provide propulsion equivalent to a typical electric vehicle. In addition, the motor, acting as a generator, can accept negative driveline torque either via the IC engine and/or the drive wheels to recharge the traction battery when its state of charge is low.

0-7803-7298-0/02/$17.00 © 2002 AACC

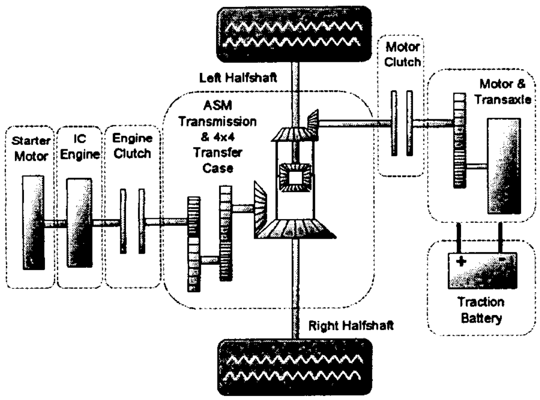

Figure 1: PHEV Powertrain

An ASM transmission is a more attractive choice than a fully automatic transmission since the former is more efficient in both performance and cost. With this hybrid vehicle configuration, the high efficiency of the automated manual can be combined with a direct drive electric motor to make a highly efficient manual transmission that shifts as smoothly as an automatic while mitigating some of the added costs of hybridization.

During a gear shift, (when the engine or engine and motor in combination power the vehicle) torque to the drive wheels is disrupted. This can adversely affect drivability if not properly managed. In a conventional automatic transmission system, the torque converter acts to dampen or smooth these fluctuations. In the ASM system, the motor is used as a torque source during the shift to mimic the action of the torque converter. The motor accomplishes regenerative braking and/or emulation of engine compression braking during downshifts. This paper presents a means of providing motor torque during upshifts. Both the amount of motor torque applied and the length of time it is applied are control system parameters that can be optimized by minimizing an objective metric of transmission shift quality.

In addition to the torque fill-in control scheme, this paper presents an overview of the PHEV control strategy, a brief discussion of shift quality and metrics, the parameter optimization process, simulation results, and vehicle data that validated the simulation.

2. POWERTRAIN MODEL

A quality dynamic model is paramount to the development of effective control strategies, especially when dealing with complex coordinated control problems such as the PHEV presented here [4]. The model is composed of all components shown in Figure 1 including stiffness and damping of shafts. A supervisory coordinated controller together with distributed controllers for the engine, clutches, ASM transmission, induction motor, and traction battery are also modeled. The coordinated controller model is directly translated into embedded C code for in-vehicle and laboratory use. Thus, the utility of a validated powertrain model is obvious.

Figure 2 (at the end of the paper) exemplifies the degree of correlation between actual vehicle data for halfshaft torque (with torque fill during shifts) to a simulation over the same drive cycle. Pedal commands captured from the vehicle data recorder were used to drive the model. Good correlation in both magnitude and frequency are evident.

Having confidence in the simulation results, many alternative control strategies and calibrations were easily developed before in-vehicle implementation.

3. HYBRID OPERATING STRATEGY

The PHEV coordinated controller provides motoring and regenerative commands to the motor controller for positive or negative motor torque and throttle blade commands to the engine controller. These commands are based on the battery's state of charge, motor speed versus torque limits, motor torque current, motor field current, transmission gear, accelerator pedal position, engine clutch state, motor clutch state, engine speed, average power at the drive wheels, shift status, estimated engine torque, and estimated engine torque available. In addition, the controller provides clutch control during braking, or hybrid operation. Braking commands are generated and sent to the brake system.

Total driveline torque may be partitioned to operate in an engine only mode, a motor only mode, or a two-traction device mode. Hybrid mode operation consists of motor only operation, engine operation, motor torque application during shifting, motor assist during power boost, and regenerative braking.

The vehicle launches in motor only mode for optimal drivability, emissions, and fuel economy. When the average power at the vehicle wheels reaches a level where operation of the engine is beneficial the conventional starter motor cranks the engine and the motor is no longer operated. Since the vehicle is already in motion, starting the engine and connecting it to the powertrain without inducing objectionable noise, vibration, and harshness poses an interesting control problem. One piece of the solution is to crank the engine during a gear shift event (generally a 1^{st} to 2^{nd} gear shift). This is useful since the engine clutch must be disengaged for the shift anyway, thereby minimizing the number of torque disruptions to the driveline.

The engine clutch uses friction to transmit torque to the manual transmission. The clutch plate friction allows the plates to slide before becoming fully engaged to prevent jerking. The conditions for engine clutch slipping are a function of engine speed, vehicle speed, and halfshaft resonance. When the engine speed is much greater than the vehicle speed, then slipping is necessary to allow the engine clutch friction to load the engine, thus reducing the engine speed to the vehicle speed level so that smooth engagement can take place. When the engine speed is much slower than the engine clutch speed, engine clutch slippage allows engine speed to be increased, via the throttle, while exposing the engine to a very small load, thus avoiding engine stall. During engagement, essential negative damping causing clutch shudder and halfshaft resonance may be present in magnitudes and frequencies may be objectionable to the driver [5]. In this case, modulation of the clutch in a variable slipping state is desirable in order to damp such oscillations.

Coordinated control of motor torque and engine clutch slip are accomplished in a manner seamless to the vehicle occupants. The result is smooth gear shifts approaching those attainable with a conventional torque converter and automatic transmission. Clutch slip control is left as the subject of another paper.

4. SHIFT QUALITY AND METRICS

One of the most important performance characteristics of automobiles equipped with automatic transmissions is shift quality. Disruption of driveline torque during gear ratio changes can result in noise, vibration, and harshness issues that can negatively impact the customer's perception of the vehicle's drivability and quality. Loud clunks and jerkiness do not translate into customer satisfaction.

Efforts to quantify shift quality have been ongoing from the early days of the automobile industry to the present. Subjective rating systems were long the industry standard whereby expert evaluators were employed to quantify shift quality. For instance, a 1 to 10 rating system can be used. Although many fine powertrain have been produced with this method, some problems with this approach are fairly obvious. These range from fundamental differences in the perception between the raters to mood and fatigue effects within a single rater. Expert raters have proven remarkably consistent in their back-to-back and even day-to-day evaluations, but not over the extended period necessary to develop a powertrain. [6]. Clearly, an objective measure of this inherently subjective phenomenon is of great value.

Several objective measures for shift quality have been investigated including peak and peak-to-peak longitudinal acceleration, jerk (time derivative of acceleration), the logarithm of peak acceleration, and the log sum of the first three acceleration peaks [7]. M. J. Griffin [8] identified a measure termed vibration dose value (VDV) that correlates well with human perception and has become somewhat of an industry standard objective metric for transmission shift quality. It is a frequency-weighted function of vehicle longitudinal acceleration and is calculated according to Equation 1 below.

$$VDV = \sqrt[4]{\int_{t_0}^{t_f} \hat{a}^4(t)\, dt} \qquad (1)$$

Where $\hat{a}$ (t) is the vehicle longitudinal acceleration, filtered according to the Butterworth bandpass filter shown in Figure 3, t_0 is the time at the start of the gear shift and t_f is the time at the shift completion [9].

Minimization of VDV is a valid goal in control law development. However, improvements in VDV must be weighed against possible degradations in fuel economy and performance feel before they can truly be classified as optimal at the vehicle level. This paper deals only with the optimization of VDV, leaving the complete powertrain and vehicle optimization for future study. In this vein, it does, however, provide a useful methodology and tool to assist in accomplishing such worthy goals.

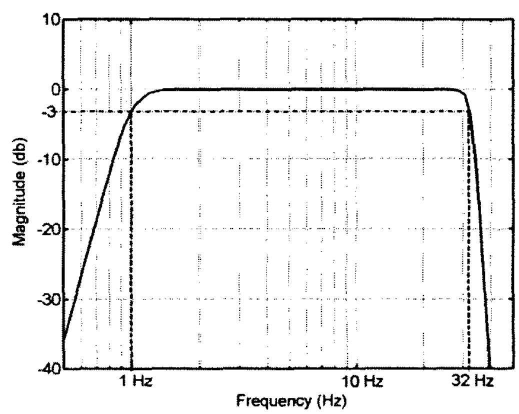

Figure 3: VDV Acceleration Filter

5. TORQUE FILL-IN STRATEGY

During an upshift of the ASM transmission, when the engine or engine and motor in combination power the vehicle, torque to the drive wheels is disrupted. This torque disruption can severely affect drivability, degrading the perceived quality of the vehicle. The effect on drivability is related to the change in both magnitude and frequency of longitudinal acceleration that occurs when torque to the drive wheels is removed or reduced due to engine clutch engagement and disengagement. The induction motor is commanded to provide a controlled amount and duration of torque during shifts to "fill-in" the lost torque caused by the engine clutch engagement and disengagement. Thus, the fill-in torque can mitigate much of the torque disruption, improving both shift quality and drivability.

In this PHEV, gear shifts do not occur in motor only operation. When the 1st to 2nd shift takes place, also the time when the IC engine is cranked, the motor is already providing driveline torque, launching the vehicle. The control strategy modulates motor torque for a period after the engine has been started but before the shift has been completed.

6. PARAMETER OPTIMIZATION

The complex, highly nonlinear nature of this control problem, not to mention program timing constraints and implementation issues, does not readily lend itself to analytical optimization techniques. Numerous simulations were performed, using the validated powertrain model, covering a discrete set of possible combinations of two critical parameters: amount of torque to be applied and length of time to apply it. In addition, considerations were made for varying acceleration profiles and which shift was taking place. VDV was chosen as the measure to be minimized.

Figure 4 (at the end of the paper) shows how VDV varies with gear shift and amount of fill-in torque provided by the motor for a typical acceleration profile. For each shift, zero fill-in torque resulted in the highest VDV, or worst shift quality, as expected. The curve shapes are similar for all upshifts except 1^{st} to 2^{nd} gear due to the significantly higher torque involved. Not surprisingly, the 1^{st} to 2^{nd} shift requires the largest fill-in torque to achieve minimum VDV: 40 Nm. Optimal values for 2^{nd} to 3^{rd} , 3^{rd} to 4^{th} , and 4^{th} to 5^{th} gears are approximately 20, 20, and 35 Nm, respectively. Some variations in optimal VDV due to vehicle acceleration exist and are easily be accounted for in the control strategy.

The other factor used to optimize VDV in this study is the length of time the fill-in torque was applied. Figure 5 (at the end of the paper) shows a typical scenario on a 1^{st} to 2^{nd} gear upshift. Again, a concave optimization function is evident, where, by inspection alone, one can surmise that the optimal application time is the center value of 0.69 seconds. From the top graph one can see that a 0.46 second application results in a significant drop in vehicle acceleration. In opposition, a 0.92 second application provided too much extra torque and caused a large positive acceleration spike. The middle value produced neither dip nor spike that would be objectionable to the driver and passengers. This fact was reflected in a minimum VDV.

Figure 6 shows halfshaft torque, measured on the vehicle, during an acceleration profile both without (upper graph) and with torque fill-in. The smoothing effect provided by the torque fill control is visibly most evident in the 2^{nd} to 3^{rd} and 3^{rd} to 4^{th} gear shifts in which halfshaft torque went negative without fill-in, but stayed well positive with fill-in.

7. CONCLUSIONS

Hybrid electric vehicles offer many features desired by modern auto owners and challenging design opportunities for automotive engineers. Hybridization does not come without cost, though. In the case presented here, the use of an ASM transmission without a torque converter reduced cost and increased efficiency. However, from a controls perspective, practical implementation of such a powertrain was not without its challenges. Development of component and coordinated control strategies and a validated powertrain model consumed a significant amount of resources, but was well worth the effort.

The development and use of metrics such as VDV is also a critical tool for the automotive engineer. The VDV metric enabled many alternatives to be examined via simulation: many more than could have practically been tested in-vehicle.

The utility of model-based control strategy development cannot be overstated. It is especially useful for complex, nonlinear systems such as the hybrid electric vehicle.

REFERENCES

[1] Bates, B. (1995). Getting a Ford HEV on the Road. IEEE Spectrum, July 1995, pp. 22-25.

[2] Cho, Jeon, Jo, Park, and Lee, "A Development of Shift Control Algorithm for Automated Manual Transmission in the Hybrid Drivetrain," Seoul 2000 FISITA World Automotive Congress, F2000A036.

[3] Lei, Niu, Ge, "A Research on Starting Control Strategy of Vehicle with AMT," Seoul 2000 FISITA World Automotive Congress, F2000A038.

[4] Cikanek, S. R., Bailey, K. E., and Powell, B. K., "Parallel Hybrid Electric Vehicle Dynamic Model and Powertrain Control", Proceedings of the American Control Conference, Albuquerque, NM, June 1997.

[5] Cikanek, S. R., Sereshteh, A., and Slicker, J. M., "Driveline Torsional Vibrations Control Method in an Electric Propulsion System", Electric Vehicle Association of Canada, Paper EVS88-045, November 14, 1988.

[6] Horste, Ken, "Objective Measurement of Automatic Transmission Shift Feel Using Vibration Dose Value", SAE Paper Number 951373.

[7] Scwab, Leo F., "Development of a shift Quality Metric for an Automatic Transmission," SAE Paper Number 941009.

[8] Griffin, M. J., Handbook of Human Vibration, London, 1990, Academic Press.

[9] Megli, T. W., Haghgooie, M., and Colvin, D. S., "Shift Characteristics of a 4-Speed Automatic Transmission", SAE Paper Number 1999-01-1060, SP-1440.

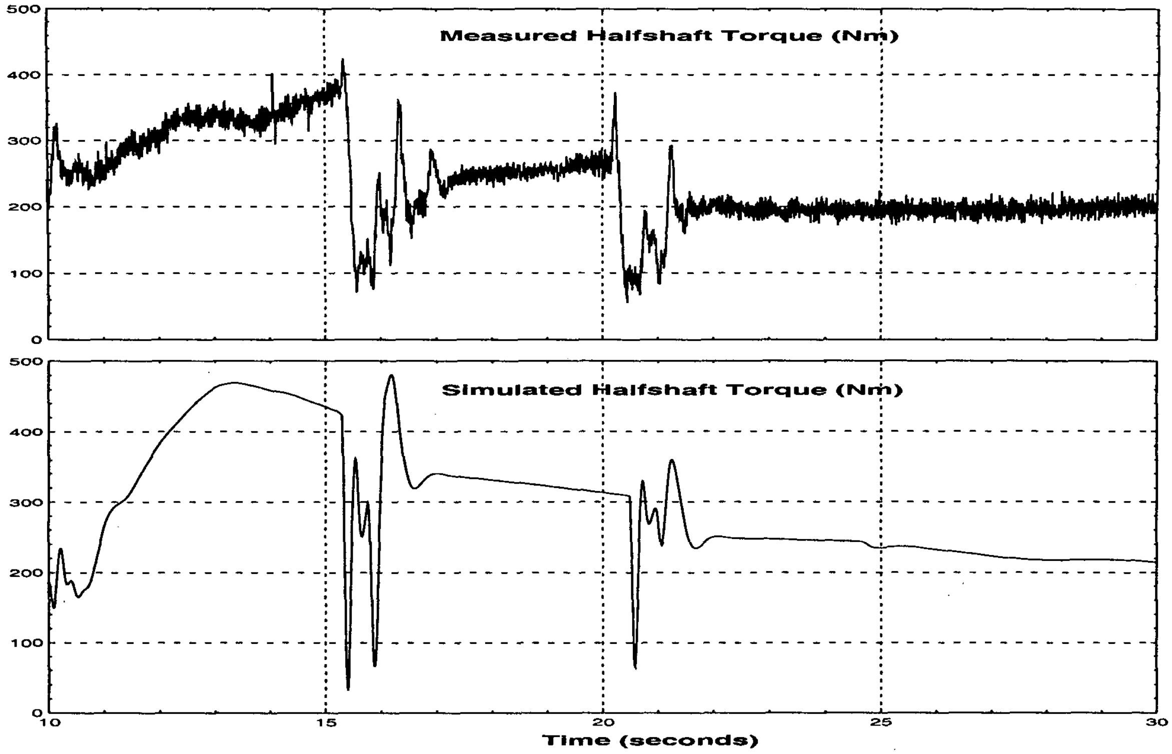

Figure 2: Actual vs. Simulated Halfshaft Torque With Fill-in

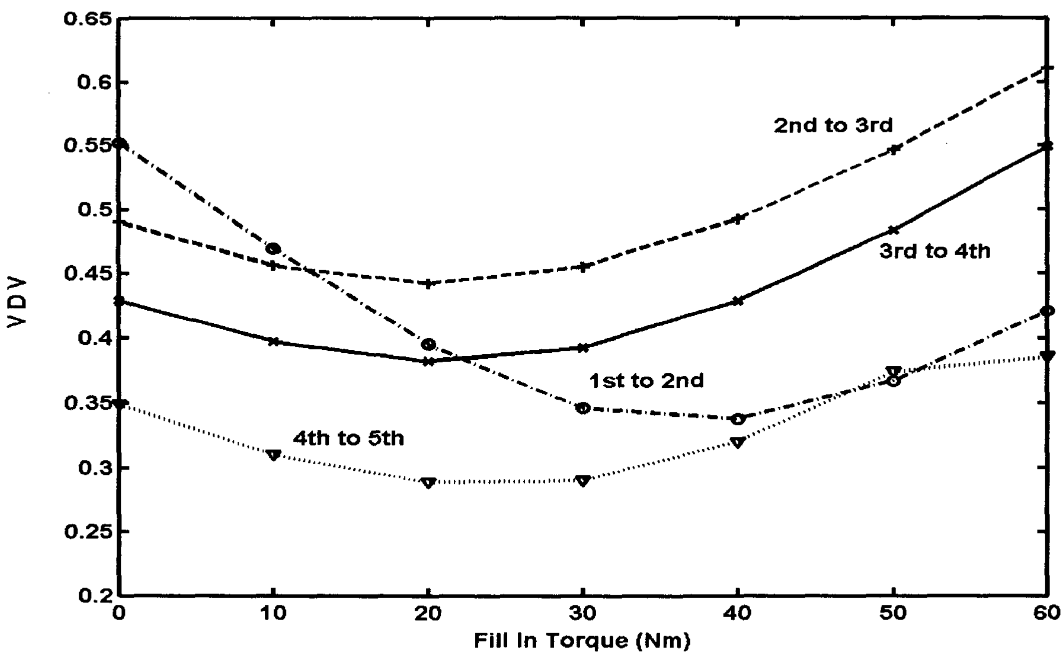

Figure 4: Shift-Optimized Fill-in Torque

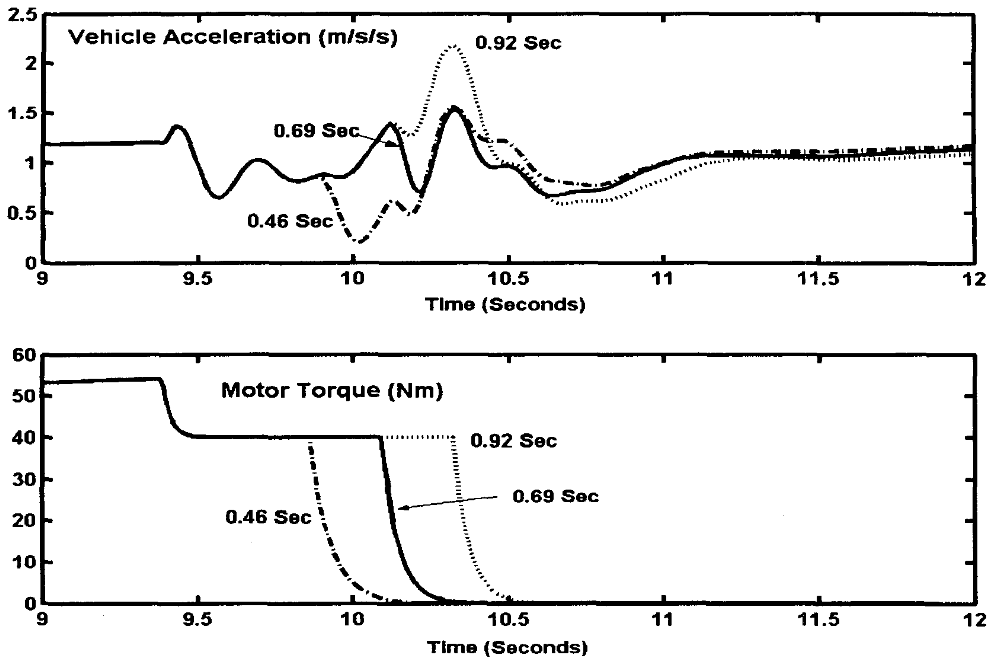

Figure 5: Optimal Fill-In Torque Application Duration

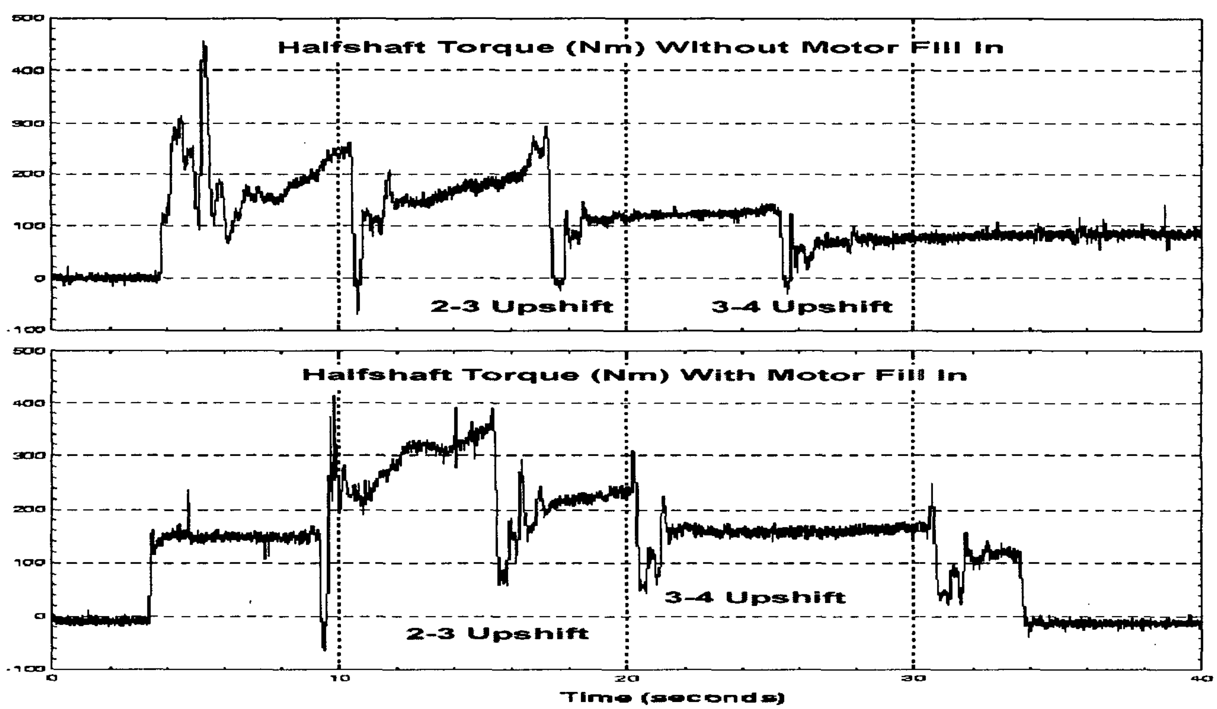

Figure 6: Effect of Torque With Fill on Halfshaft Torque