

Torque Converter Clutch Optimization: Improving Fuel Economy and Reducing Noise and Vibration

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ABSTRACT

The torque converter and torque converter clutch are critical devices governing overall power transfer efficiency in automatic transmission powertrains. With calibrations becoming more aggressive to meet increasing fuel economy standards, the torque converter clutch is being applied over a wider range of driving conditions. At low engine speed and high engine torque, noise and vibration concerns originating from the driveline, powertrain or vehicle structure can supersede aggressive torque converter clutch scheduling. Understanding the torsional characteristics of the torque converter clutch and its interaction with the drivetrain can lead to a more robust design, operation in regions otherwise restricted by noise and vibration, and potential fuel economy improvement. The objective of this paper is to present a generalized integration summary for torque converter clutches (TCC) to enable aggressive apply at high engine torques and engine speeds below 1500 rpm without adversely affecting noise and vibration (N&V) performance. The focus is on optimizing existing damper technologies found in a large percentage of current production automatic transmissions. The overall goal is to demonstrate that through proper hardware selection and TCC calibration, a balance between N&V and fuel economy can be achieved. A validated lumped parameter modeling technique for optimizing torque converter clutch hardware that comprehends the complete powertrain and driveline system is used to investigate required TCC hardware. A torsional isolation metric across the powertrain is presented for comparing the performance of various damper designs. For operating points with inadequate isolation a controlled amount of slip across the torque converter clutch is required to increase isolation. An analytical methodology for minimizing the amount of slip required to satisfy noise and vibration targets and maximize fuel economy is reported. The

effect of gear state, torque converter slip and power delivered to the driveline on fuel economy are also discussed based upon powertrain dynamometer measurements.

INTRODUCTION

FUEL ECONOMY AND N&V CONSIDERATIONS

Maximum fuel economy is determined by the thermodynamic limits of the internal combustion engine, while parasitic losses associated with the vehicle and the individual components of the transmission and driveline act to further reduce fuel economy. Drivetrain related losses can be diminished by optimizing hydraulic pumps, planetary gears sets, clutch packs, or overall transmission design by increasing ratio spread and the number of fixed gear states. The torque converter represents a significant source for improving fuel economy since it operates with efficiencies ranging from zero to just below 100 percent. When a lockup clutch or torque converter clutch (TCC) is included, efficiency is increased to 100 percent with full lockup or a slight loss in efficiency with a controlled amount of slip across the TCC commonly referred to as electronically controlled clutch capacity (ECCC) [1]. The recent design trend is to displace more of the hydrodynamic circuit of the torque converter with TCC damper hardware in proportion to the amount of time scheduled per function.

Aggressive scheduling of the TCC, locked or controlled slip, can improve fuel economy, but can adversely affect drive quality and perceived noise and vibration (N&V), [2, 3, 4, 5]. From a drive quality perspective, degradation in throttle response can be noted because of reduced engine speed and turbine torque availability. N&V becomes a primary concern as attenuation of engine torsional vibration are significantly reduced as the torque converter transitions from

hydrodynamic to TCC operation [3 and 6]. Adequate design of the TCC damper and TCC schedule with respect to the torsional response of the vehicle's drivetrain can alleviate objectionable N&V [2, 3, 4, 5 and 6].

OPTIMIZING TORQUE CONVERTER CLUTCH HARDWARE

DRIVELINE TORSIONAL BEHAVIOR

Engine combustion and inertia torque provide source excitation for N&V transmitted via two paths to the vehicle: 1.) powertrain structure and 2.) rotating components of the driveline. Vibration through the powertrain structure is dependent upon mount design, exhaust structure and exhaust system hangars. The driveline path will be the focus of this paper as the response of powertrain structure is dominated by torque reaction of the slider-crank mechanism of the engine and is only loosely coupled with driveline torsional behavior.

The TCC damper is the primary isolation device between the engine and the drivetrain, requiring considerable engineering foresight for proper integration. Since the TCC damper is a torsional spring - inertia system, it will have a resonance that must occur at a frequency far removed from its normal intended operating range. The TCC damper must provide sufficient isolation of engine torsional vibration to minimize force inputs to the vehicle via the driveline. When sufficient isolation cannot be achieved with a locked TCC, an appropriate amount of TCC slip should be used to add damping and improve isolation.

The driveline torsional modes of interest are the TCC damper mode, turbine mode and rear differential or solid rear axle mounting modes; see [6] for mode descriptions. The first driveline torsional mode, referred to as chugger or surge, occurs too low in the frequency-speed range that it is typically only a concern during transient maneuvers. In L4 cylinder applications, the TCC damper mode occurs in an engine speed range where an aggressive TCC schedule and shift pattern makes N&V particularly problematic. For V6 and V8 applications, the TCC damper mode appears much lower in speed engine, far removed from the range of TCC apply. The turbine damper mode can be a significant N&V risk for V6 and V8 applications as it occurs in the main engine speed range for TCC operation. Historically, turbine damper modes have only been a concern on RWD applications since the transmission input (turbine) shafts are longer compared to FWD transmissions. Rear differential (RDM) or axle mounting modes are a concern for RWD applications where high torsional vibrations at the prop shaft may excite pitch or roll modes that are dependent upon the design of the mounting system.

TORQUE CONVERTER CLUTCH

To facilitate improved efficiency of the torque converter a lockup TCC was added in the late 1940's [7] and became standard on nearly all modern torque converter applications in the late 1970's [9]. The TCC is a mechanical device that bypasses the hydrodynamic circuit of the torque converter. A conventional TCC includes a friction plate connected to a spring isolator system attached to a drive hub coupled to the turbine. The purpose of the spring isolator, or damper, is to attenuate engine firing torque pulses to minimize excitation of driveline and chassis components.

The torque converter clutch is typically applied in two distinct operating modes: 1.) fully locked and 2.) with a controlled amount of slip, [1 and 3]. For complete TCC lockup, a sufficiently high pressure is applied to ensure a no slip condition. As pressure is applied to the pressure plate, engine speed will decrease until it matches exactly turbine speed once the clutch capacity matches engine torque. All engine torque is then carried by the clutch and transferred to the transmission without loss.

During controlled TCC slip, torque is split between the hydrodynamic circuit and the TCC. For relatively small slip values, speed ratio, SR , will be greater than the coupling point and torque ratio, TR , will be unity. Engine torque will equal transmission input torque and is the sum of hydrodynamic torque and clutch torque. For large slip values, the operating SR may drop below the coupling point of the converter resulting in torque multiplication. Under this condition, engine torque will not equal transmission input torque. A summary of the torque distribution for the three modes of operation for a torque converter with a TCC and controlled slip capability is shown in Figure 1.

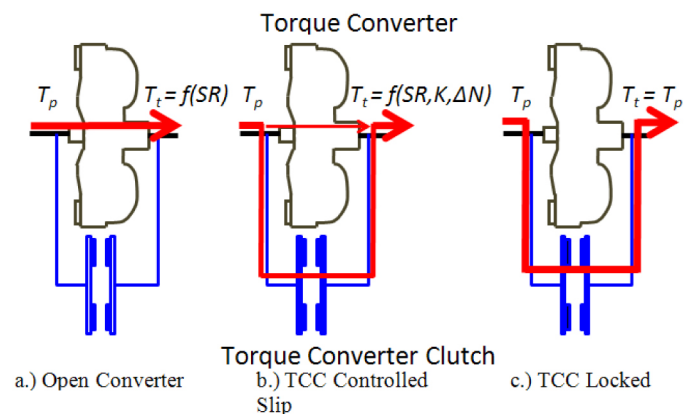


Figure 1. Torque distribution for torque converter and TCC a.) Open b.) TCC controlled slip c.) TCC Locked.

TORSIONAL VIBRATION ISOLATION METRIC

In order to discuss optimizing TCC hardware a suitable performance metric with respect to N&V must be selected for comparison of different designs. This process can be ambiguous, as many options and process exist for assessing N&V improvements through hardware modifications. Target metrics that encompass known sensitivity of actual vehicle hardware or torsional vibration limits of the drivetrain are most preferred, but require apriori knowledge of N&V sensitivity. Sensitivity testing (a/T or L_p/T) of physical hardware or rigorous FEA and CAE modeling is the best way to acquire this information. An alternative approach utilizes historical vehicle and drivetrain sensitivity to torsional vibration to formulate a set of generic isolation metrics specific to various engine and driveline configurations. This method eliminates the need for physical hardware and allows engineering work for the TCC damper to progress early on in the powertrain development process. Using such a set of extrapolated isolation metrics may result in conservative predictions of isolation as improvements to vehicle and driveline sensitivity for future platforms are not taken into accounted.

For this investigation, a generic isolation approach was selected for simplicity and applicability to future powertrains. The isolation metric compares the relative magnitude of engine torsional excitation and the torsional response at the output of the transmission tracked on primary engine firing order. Although higher engine harmonics can be analyzed, the first engine harmonic produces the highest torsional vibration and corresponds to the majority of N&V complaints. The isolation target is a function only of engine and drivetrain architecture, e.g. number engine cylinders and FWD vs. RWD and is independent of engine torque. Alternatively, the isolation target can be viewed as a loss function across the powertrain since the requirement is a fixed offset between engine and transmission independent of operating torque or gear state. [Figure 2](#) is a graphical representation of the isolation metric for a FWD L4 application at two engine torques.

Four cylinder engines produce higher torsional vibrations than V6 or V8 engines and consequently have a more aggressive isolation target. FWD applications have the added benefit of the final drive gear reduction within the transmission, further reducing torsional velocity by final drive ratio, resulting in a more stringent isolation target at the output of the transmission compared to RWD transmissions. Isolation targets for RWD applications should be increased in frequency ranges of known or estimated rear differential mounting modes to avoid potential N&V issues. The isolation targets utilized for this investigation were obtained by surveying of a range of vehicle and powertrain configurations and subjective evaluation of N&V relative to measured

isolation. The actual isolation targets used in this investigation are not reported due to competitive advantage.

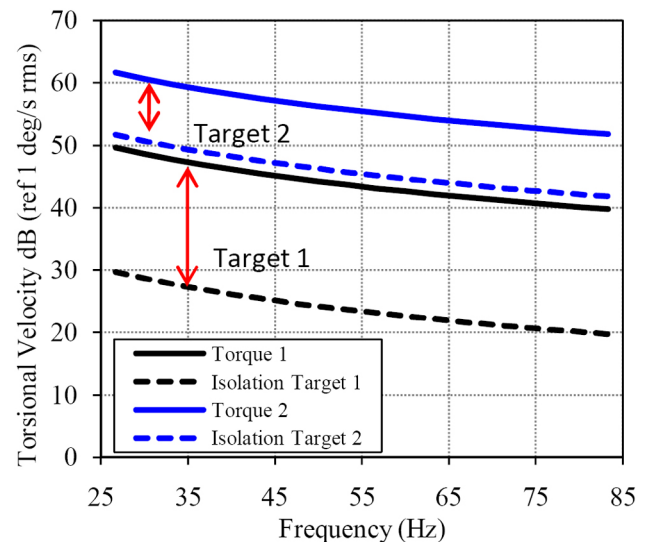


Figure 2. Example torsional isolation target for L4 engine at two torques.

MODELING AND ANALYSIS TECHNIQUE

A lumped parameter model technique is used to represent the TCC damper, transmission, driveline and vehicle throughout this paper. Details regarding the modeling technique are omitted for length and competitive reasons, but are very similar to those reported previously in the literature with much success; see [4, 6 and 9] for examples. Contiguous rotating elements of the torque converter, clutch damper, automatic transmission, and vehicle driveline are represented as discrete inertia's connected by shafts of finite stiffness, clutches with friction and gearing. The lumped parameter model also includes nonlinear elements such as hysteresis in the TCC springs. In this investigation, the number of degrees of freedom (DOF) is substantially increased from previous studies to improve accuracy and represent a majority of the torsional modes of the powertrain and driveline.

Excitation for the driveline model can be provided by measured or computed cylinder pressure data or by engine kinematic relationships [6]. For the purposes of this investigation, a generalized engine excitation model was developed by surveying a range of displacements and combustion types. The model was generated by curve fitting the ratio of harmonic torque to mean torque and fitting it to number of cylinders, combustion type, reciprocating mass and stroke. The engine excitation model estimates the first and second harmonic of gas and inertia torque with proper phase relationships.

Model correlation is demonstrated in Figure 3 for a L4 FWD sedan and Figure 4 for a V6 RWD sedan. The vehicle data was collected on a chassis dynamometer, operating a constant engine torque while sweeping engine speed with the TCC completely locked. In either case, it can be noted that good correlation, on the order of ± 3 dB, is achieved for both engine and transmission torsional velocity for first harmonic of engine firing order. This modeling approach provides sufficient correlation to enable accurate decision making for TCC hardware design and TCC slip calibration.

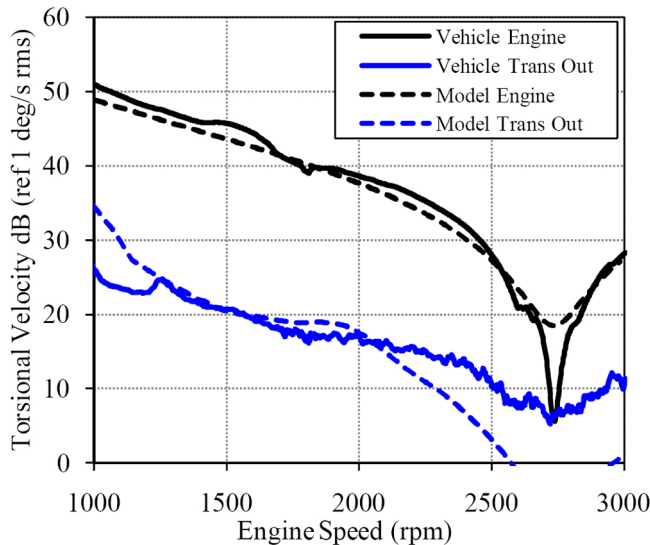


Figure 3. Lumped parameter model correlation 2nd order torsional velocities for FWD L4, 105 Nm, six-speed transmission, 4th gear, TCC locked.

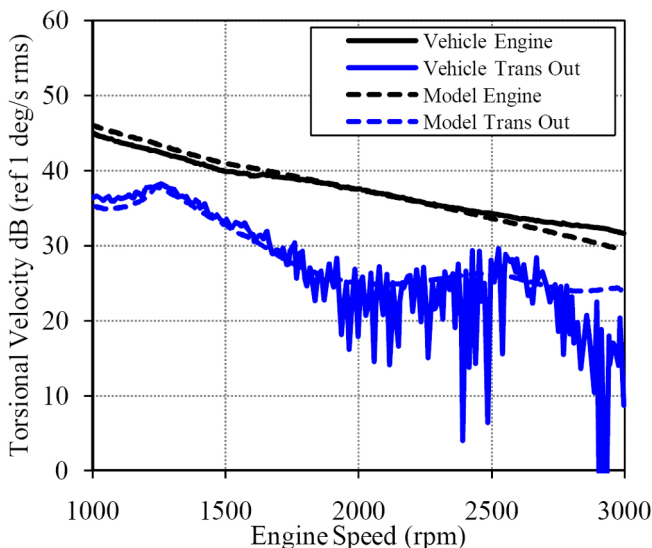


Figure 4. Lumped parameter model correlation 3rd order torsional velocities for RWD V6, 225 Nm, six-speed transmission, 6th gear, TCC locked.

TCC OPTIMIZATION

A considerable amount of literature exists on TCC damper design to increase torsional isolation and reduce its torsional resonant frequency [2, 3, 4, 5, 6]. The ability to optimize the TCC damper for every application is constrained by packaging, mass and rotating inertia and cost considerations. The major parameters for tuning TCC design have been spring rate, travel, hysteresis, TCC damper architecture (arrangement of springs and inertia's) and controlled slip. Since slip results in a loss of fuel economy, it is usually the last parameter to be modified. A systematic approach to analyzing the effect of each of these parameters is provided along with measured vehicle data to confirm model observations.

SPRING RATE

A fundamental property of the TCC is the torque capacity curve similar to that shown in Figure 5. Most modern TCC dampers either are a single rate or step rate design. For step rate designs the change in rate, commonly referred to as the “knee,” and the ultimate torque capacity of the damper are determined per engine application. Typically, the knee capacity is selected to occur at roughly at 80 to 100 percent of maximum torque for gas engines and 120 to 140 percent of maximum torque for diesel engines. The ultimate torque capacity for a single rate or step rate design is typically set at 125 to 150 percent maximum torque depending on the engine application.

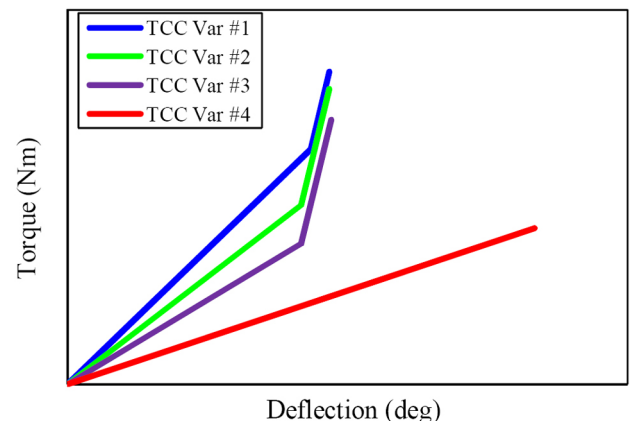


Figure 5. Torque - deflection curves for TCC damper spring rate investigation.

Improved isolation is derived by lowering the TCC damper mode frequency and increasing compliance. This is achieved with increased travel and lower spring rates that form a class of TCC dampers referred to as long-travel dampers (LTD) [4, 6 and 9]. The TCC damper designs simulated for the effect of spring rate are represented in Figure 5. The basic damper design is an outer diameter (OD) arc-spring. The first three damper variants maintain identical travel characteristics but