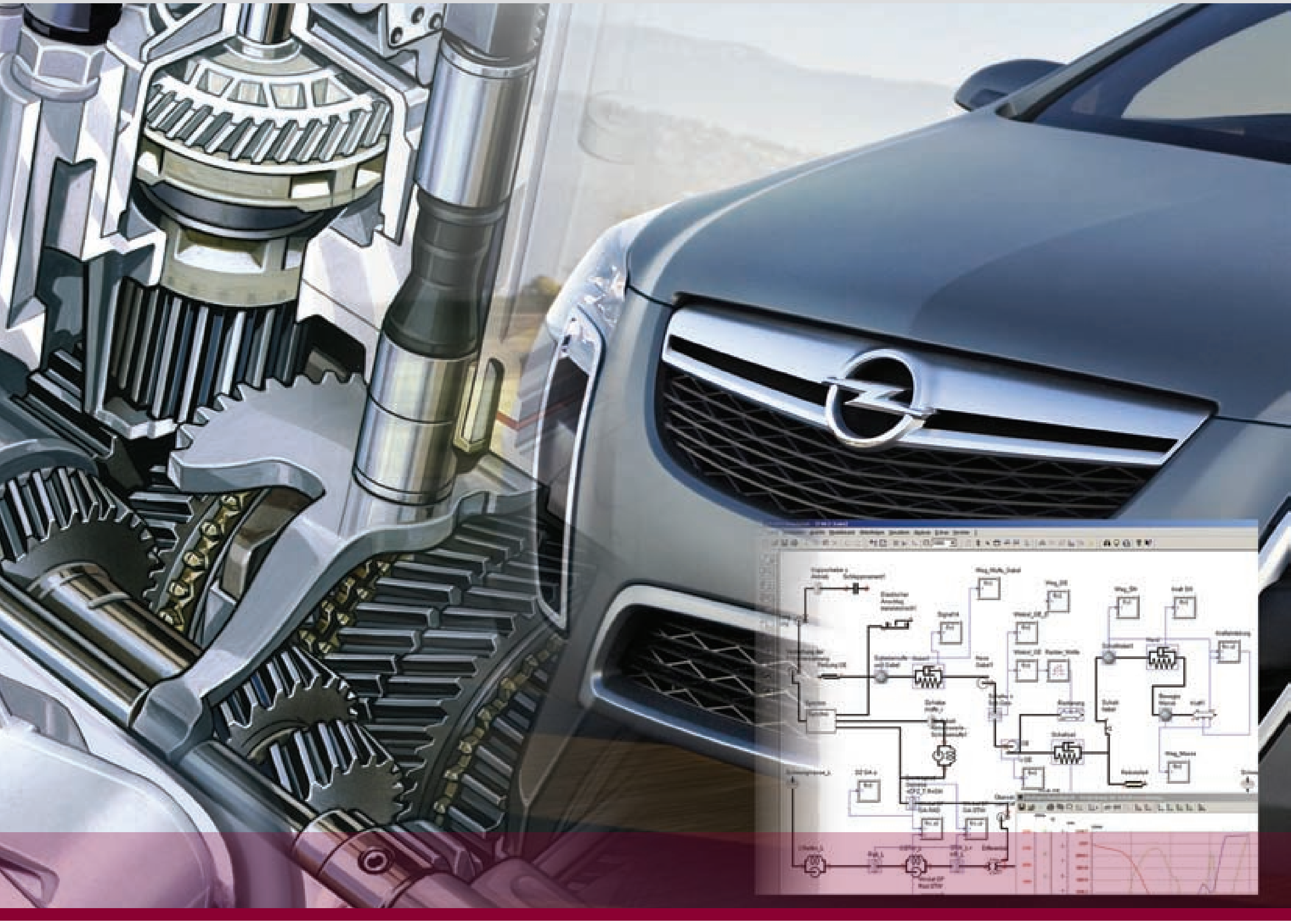

Development of Shift Comfort for Manual Transmissions in Passenger Cars

GM Powertrain has in close cooperation between testing and simulation areas established a development method for shift comfort analysis for manual transmissions in passenger cars. The focus has been to improve the process from the first measurement and simulation downwards to the implementation of a design measure into production. The standardization of how to measure and how to handle data in conjunction with good analytical methods and accurate simulation has been important factors for this work.

1 Introduction

In the past, the focus in transmission development used to be mainly on durability of the components. Despite that shift quality has improved significantly in the last years, increasing customer expectations have made it necessary to further change the focus in transmission development towards shift quality. Regarding shift quality, it is important that the mostly subjective requirements are decomposed into targets for different areas and further into measurable, quantitative targets. At GM Powertrain, shift quality has been divided into four sub areas; shift effort, exactness, NVH and shift comfort. A large portion of the properties for each of these groups are related to basic design and can be assessed in the early stages of the design and development process. Nevertheless, for shift comfort and NVH deeper understanding of the complete shift system behavior from the synchronizer to the shift lever is necessary.

This article mainly covers shift comfort related aspects and demonstrates how GM Powertrain works with shift comfort at concept level and further how detailed simulation and analysis tools are developed and utilized.

2 Shift Quality Definition

This chapter introduces the four different aspect of shift quality on a more detailed, quantitative level; furthermore, the synchronization process is explained briefly since it is essential for the shift comfort discussion.

2.1 Shift Operation

During the first phase of the synchronization process the driver pulls out the previous gear and moves the lever into next gear passing the neutral position, see **Figure 1**. During this phase, the force in the shift system is almost entirely defined by detent mechanisms. The characteristic of these devices is intended to make the driver aware of lever position, that means give some feedback. It helps the driver to notice when the previous gear disengages and when the lever reaches neutral position. The force amplitude during this first phase is almost independent of shift lever velocity.

The second phase covers the synchronization of transmission input and output speed. During this phase, the force in the shift system depends on gear lever velocity, engine and vehicle speed, synchronizer capacity and input shaft inertia. The synchronization impulse is the main evaluation criterion and it is defined as the force-integral over time during this second phase. The end of this second phase is characterized by the so called blocker release. Since synchronization is completed, the friction torque in the synchronizer itself drops to zero and releases the blocker system, the synchronizer ring can be rotated and the shift sleeve is allowed to travel to move towards its target position.

The third phase is the so-called engagement. The synchronizer sleeve leaves the blocking position and enters – after a short time of free movement, which is in some sources named as a separate phase, for example [1] – the engagement ring. This passage of entering the engagement position can occur in many different ways. The character of this indexing can span from a clean engagement, where the whole shift system snaps into gear distinctly, to a refractory motion where the sleeve bounces over a few engagement ring teeth before engaging. The latter cause harsh reaction force peaks, which propagate through the shift system up to the gear lever knob.

The fourth and final phase is when the synchronizer sleeve reaches the end stop and shift is completed as to be seen in Figure 1. To ensure driver feedback, the end stop shall have a distinctive rigidity indicating the completion of the gear change.

2.2 Shift Effort

The shift effort target embraces both static and dynamic shift properties. The static properties have targets for shift- as well as select-direction. Force targets are defined in an early design phase and the values are influenced by shift system ratio, friction and detent forces. Examples of targets are:

- out of gear force
- into gear force
- reverse lift ring force.

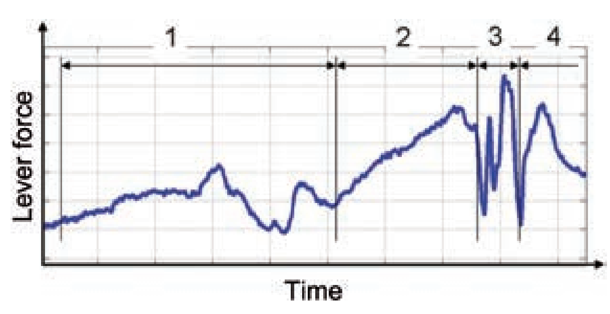

Figure 1: Tactile force during manual gear shift

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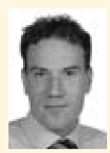

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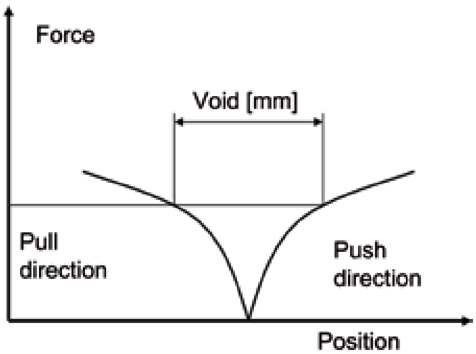

Figure 2: Shift lever void

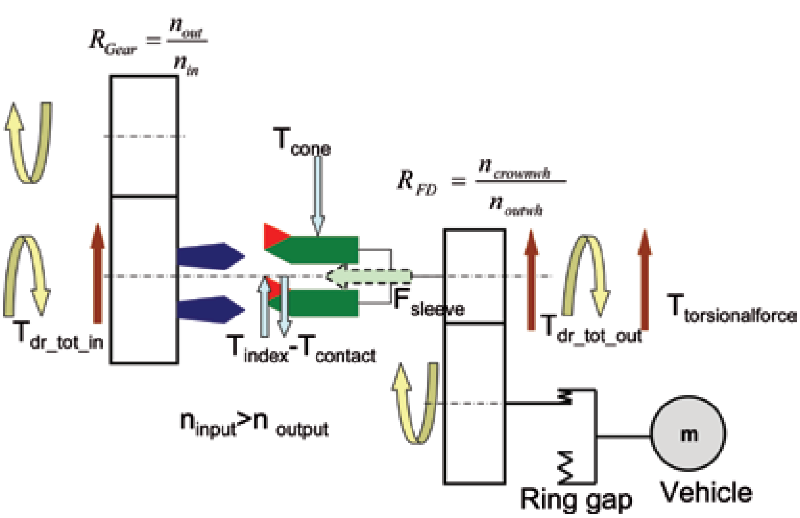

Figure 3: Transmission and driveline during synchronization; cone torque winds up the driveline

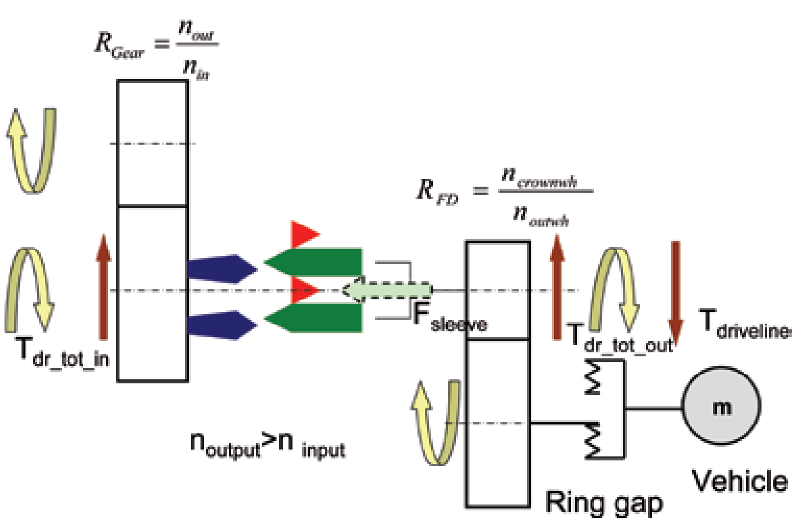

Figure 4: Transmission and driveline at start of engagement; driveline unwinds

The dynamic shift target is defined as an impulse, Figure 1. Target values are again defined in early design phases. Normally influencing properties are known at this stage like input shaft inertia, shift system ratio, shift system efficiency and gear ratio. These together with the synchronization impulse are the main targets considered when determining the required synchronizer capacity.

2.3 Shift Exactness

Good exactness helps the driver to select gear, it is the net result of friction, lash and stiffness in the complete shift system. Exactness is subdivided into in-gear voids and neutral void, see **Figure 2**. All requirements on the voids are defined depending on the shift force amplitude at the gear lever knob.

2.4 NVH

Good NVH properties imply that the transmission installation causes neither noticeable vibration nor emits audible noise. The noise or rattle is measured in dB or in m/s². The NVH targets are for example:

- cable rattle
- shift lever vibration
- shift noise.

2.5 Shift Comfort

The shift comfort target is defined in terms of gear lever force peaks due to double bump and scratch during the engagement period of shift sleeve and engagement ring. The rating is based on number of peaks and peak amplitude.

3 Scratch, the Root Cause of Comfort Problems

A complex chain of events takes place right after synchronization as schematically sketched in Figure 3 and Figure 4. The sleeve leaves the blocker ring and starts passage into the engagement ring to finally engage the gear. Since there is some torque acting in opposite directions on the input and output shafts, the synchronizer components tend to rotate in relation to each other for a very short time after synchronization. The relative speed increases impact force, when the sleeve enters the engagement ring and the sleeve may even bounce several times before settling in the teeth pockets. The impact, the bouncing and the sudden changes in kinetic energy cause reaction force peaks that propagate through the shift system and finally reach the drivers hand. This is known as poor shift comfort. A number of properties contributes to generate these reaction forces: shaft inertia, shaft drag, drive shaft stiffness, driveline lash and fork force due to knob force, shift system stiffness, detent characteristics etc.

Shift comfort problems prevail when shifting from low gears up, for example 2-3. The up-shift scratch phenomenon is caused by several factors. Driveline lash is an important parameter, which causes a sudden increase in the speed of the output shaft. During an up-shift, the driveline is positively driven by the input shaft deceleration torque through the synchronizer, see **Figure 3**. The synchronization torque winds the driveline towards the positive side of the lash.

When synchronized speed is achieved the torque from the synchronizer drops to zero and the driveline unwinds due to reaction force from the driveline and drag. After the back lash passage is complete the driveline drives the gearbox on the negative side of the lash and will cause a sudden change in output shaft speed, see **Figure 4**. If the shift is not finalized when this occurs, the risk of scratch is high and if the sleeve has not passed the blocker ring it will be caught by the latter one on the down shift side, the result will be a blocker flip. If the sleeve is not able to pass the blocker ring it is called blockage.

4 Shift Comfort Development

During early development phases computational methods are used by GM Powertrain to optimize gearbox and integration concept regarding shift quality. Shift effort and exactness are evaluated using accurate math based tools before hardware is available. Shift comfort and NVH are more difficult to assess. Design directions are determined with the aid of simulation during the concept phase. Properties, which are known to influence shift comfort, are included in the requirements for new products together with defined targets. These are carefully tracked throughout the whole development process. Properties, which are considered as having a major influence, are:

- Inertia of shafts, gears and clutch disc
- Drag torque
- Shift system efficiency
- Shift system ratio
- Teeth geometry of sleeve, engagement ring and blocker ring
- Synchronizer capacity.

The design parameters are defined in different stages of the development process. Inertia and drag torque are driven by the layout of the transmission and are therefore calculated or measured early in the process. It is important to keep the affected inertia and drag torque for each gear as low as possible. The next step is to determine the required synchronizer capacity using well established shift impulse targets for a given inertia, drag torque and total shift system ratio. The synchronizer roof angle is set so that the ratio between synchronizer torque and index torque is well balanced. The shift system ratios in the transmission system, teeth geometry and shift system are parameters which are defined latest in the project and are those used when tuning the complete shift actuation system.

Once hardware is available, the system undergoes fine tuning. Precise measurements as shown as an example in **Figure 5** are performed to understand the dynamic behavior of the system in detail; a detailed shift comfort simulation model is developed. Shift comfort simulation will help the development process both with understanding complex system mechanisms and predict the outcome of design proposals. The shift comfort model evolves during the whole lifetime of transmission and vehicle.

5 Data Acquisition

Shift comfort measurements are usually carried out on a chassis dynamometer. On the dynamometer, shifting gears can be done more consistently compared to road shifts since the driver only has to concentrate on shifting gears. The gearshift lever is equipped with a knob which measures force and displacement. Input and output shaft speed is also measured and considered very essential. To perform a thorough investigation, more sensors are used forming a complete set-up:

- knob force and displacement (in shift and select direction)
- cable force and displacement
- internal shift mechanism, force and displacement
- input and output shaft speed
- oil temperature.

To obtain a full spectrum of the shift comfort performance for all shifts (1-2-1, 2-3-2, 3-4-3, 4-5-4, 5-6-5) the following parameters are varied throughout the test:

- shift force from a lowest possible limit to a level where double bump does not occur
- input shaft speed 2000 and 4000 rpm
- oil temperature −10 to +70 °C.

6 Data Analysis

In this chapter the method of post-processing the data obtained by measurement and simulation is explained, emphasis is put on the automatic detection of key criteria in the time dependent data sequences.

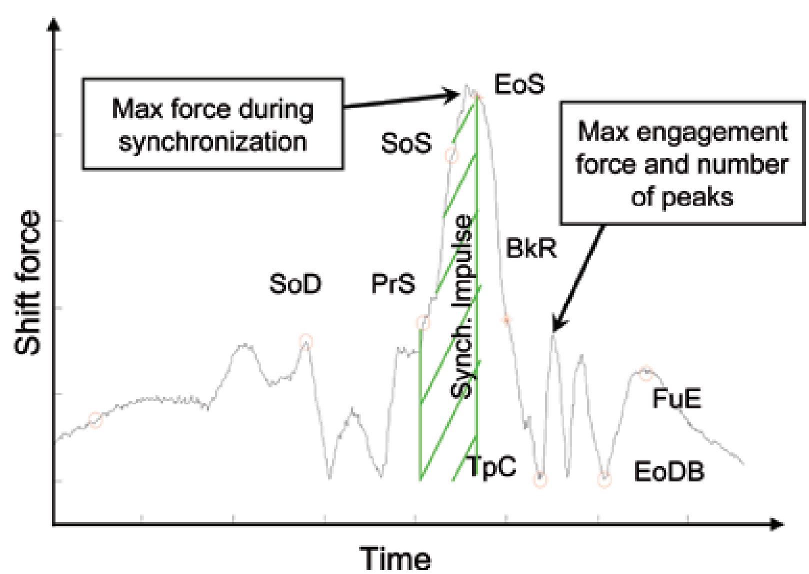

Figure 5: Shift measurement with identified characteristic events

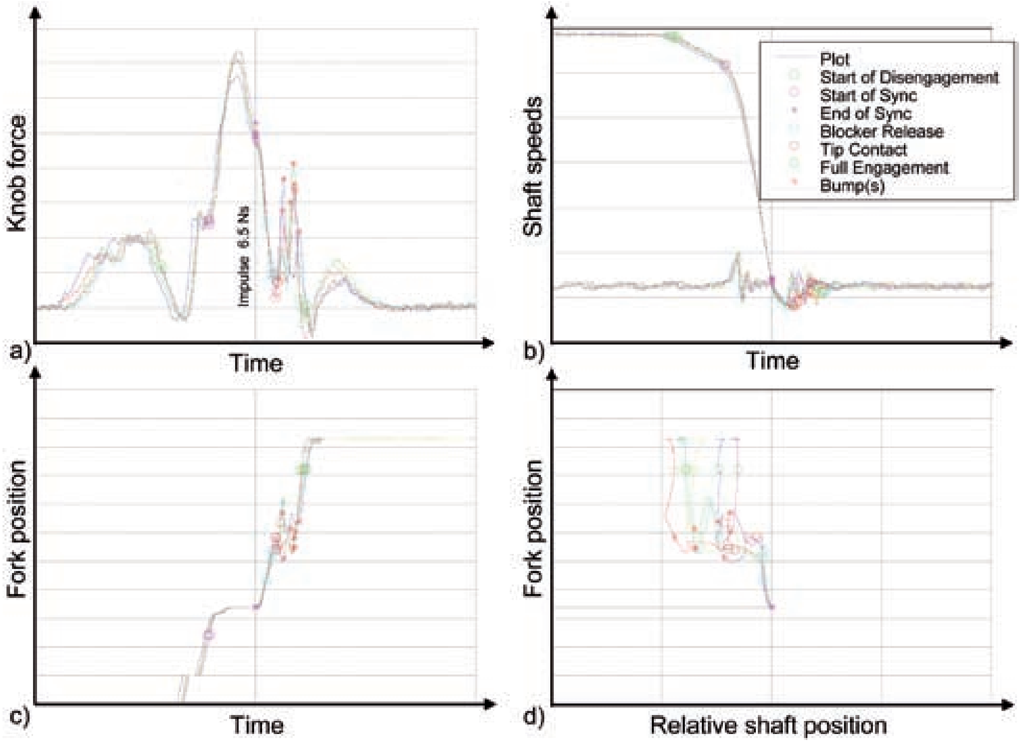

Figure 6: Shift plot tool: a) knob force vs. time, b) shaft speeds (seen from input shaft) vs. time, c) fork position vs. time, d) fork position vs. relative angular synchronizer position (as seen from input shaft)

6.1 Event Detection

The next step after data acquisition is data analysis. GM Powertrain has developed in-house methods in this regard to achieve flexibility and good control of the process. The first part of analysis is to split the measured data into individual shifts and detect events for each shift. The events are used as a starting point or boundaries for more advanced analysis. The following events are detected:

- SoD: Start of Disengagement is when the disengaging synchronizer separates, start of first phase.
- PrS: Start of Pre-Synchronization is when the struts index the blocker, beginning of second phase.
- SoS: Start of Synchronization is when a substantial sync torque develops, in second phase.
- EoS: End of Synchronization is when a relative synchronizer rotation ceases, indicating end of second phase.
- BkR: Blocker Release is when the sleeve can pass through the blocker ring since the blocking moment has dropped to zero, end of second phase.
- TpC: Tip Contact is when sleeve impacts into engagement ring, critical event in third phase.
- EoDB: End of Double Bump is the end of sleeve engagement into the engagement ring, sleeve enters back-taper.
- FuE: Full Engagement is when sleeve settles in engagement ring teeth pockets, end of third phase.

Event detection is done automatically, but if important measured information is missing or hard to identify, event detection can be performed manually. During analysis a few important measures are quantified:

- double bump force, that means maximum knob force during engagement
- maximum knob force during synchronization
- synchronization impulse, that means knob force time-integral during synchronization
- number of knob force peaks during engagement
- knob back-travel, that means sum of all backward knob motion during engagement
- double bump ratio, that means ratio between double bump force and max knob force.

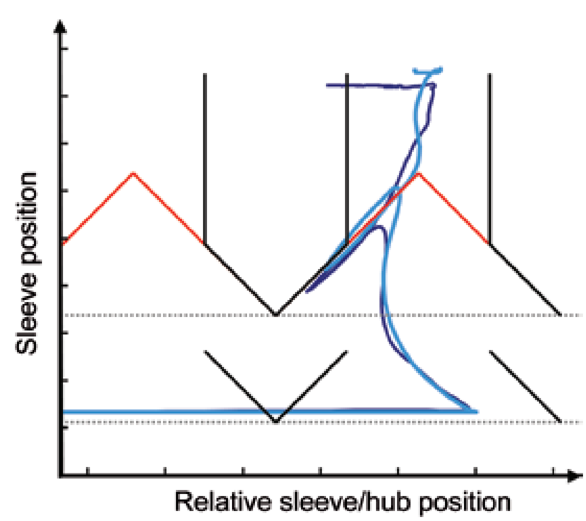

Figure 7: Early shift impact plot tool showing measured and simulated sleeve trajectories into engaged position

6.2 Shift Plot of Measurements

The shift-plot tool illustrates the most important characteristics of one or several shifts as shown in **Figure 6**. The shifts are centralized around the end-of-synchronization event to facilitate comparison.

6.3 Shift Impact Plot

The sleeve trajectory during engagement is calculated from very accurate shaft speed measurements. This is an illustrative way to gain an understanding of the mechanism behind shift comfort issues, **Figure 7** and **Figure 8**.

6.4 Shift Comfort Tool

GM Powertrain has developed an algorithm for evaluating shift comfort. The algorithm rates shifts according to the usual ATZ-scale evaluation from 1 (no function) to 10 (no negative effects to be detected even by trained personnel). The rating depends on several things but most important is the trade-off between double bump and back-travel. The latter makes the rating less sensitive to how the driver holds the knob. Some drivers hold the knob loosely, which leads to more back travel and less double bump. This happens since the driver allows the knob to move backwards. Holding the knob firmly leads to the opposite effect, high double bump force and less back-travel. Thus the calculated rating shows the following dependencies:

ATZ-Rating = f(synchronization impulse, max force, number of peaks, back travel, ...)

The rate function is implemented in a tool, which is capable of making an evaluation of one or more shifts. The tool also presents other valuable data concerning key metrics of the shift.

6.5 Shift Comfort Graph

The double bump plot is a scatter plot as in **Figure 9** showing a double bump ratio or shift comfort rating according to the GM Powertrain algorithm. By handling measured and simulated data consistently, it is possible to effectively analyze the process with little effort. The measurement and processing methodology helps to more effectively develop analysis approaches as large datasets can be statistically examined with little effort.

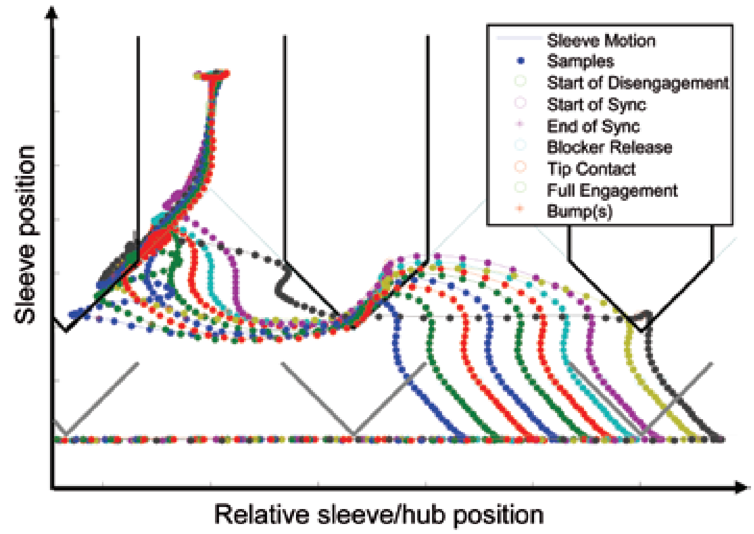

Figure 8: Shift simulation with different initial relative synchronizer positions

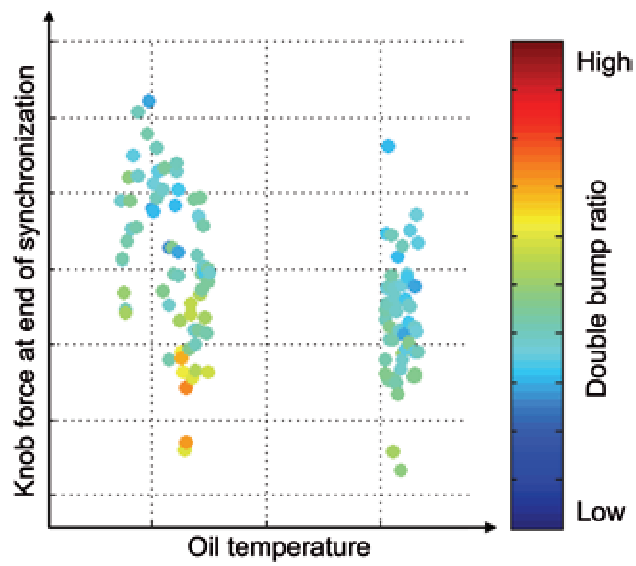

Figure 9: Scatter plots in three dimensions: double bump ratio versus oil temperature and knob force at end of synchronization

7 Shift Comfort Simulation

Computer simulation of the shift process is necessary for achieving a better understanding of the mechanisms relevant for shift comfort. Creating a Multi Body Simulation model (MBS) as schematically shown in **Figure 10** of the complete transmission emphasizes the relevant physics. The model helps to understand the root causes of dynamic problems since allowing for deeper insight compared to measured data alone. Simulation has the advantage of being 100 % consistent with parameters that are considered as noise under full control.

Typical noise is how the driver interacts with the gearshift knob and the relative angular position of the synchronizer. GM Powertrain has come to the conclusion that due to the randomness of the angular position roughly a dozen simulations must be done for one shift case, with different initial position for each run. Figure 8 shows engagement for one simulation case. It is evident that one shift case may have a big variation in shift comfort result.

7.1 Simulation Model Build

The MBS model for shift comfort simulation is extensive and contains sub-models representing driveline, gearbox, shift system and driver. It is a one-dimensional model, built by systems of masses coupled with partially non-linear springs and

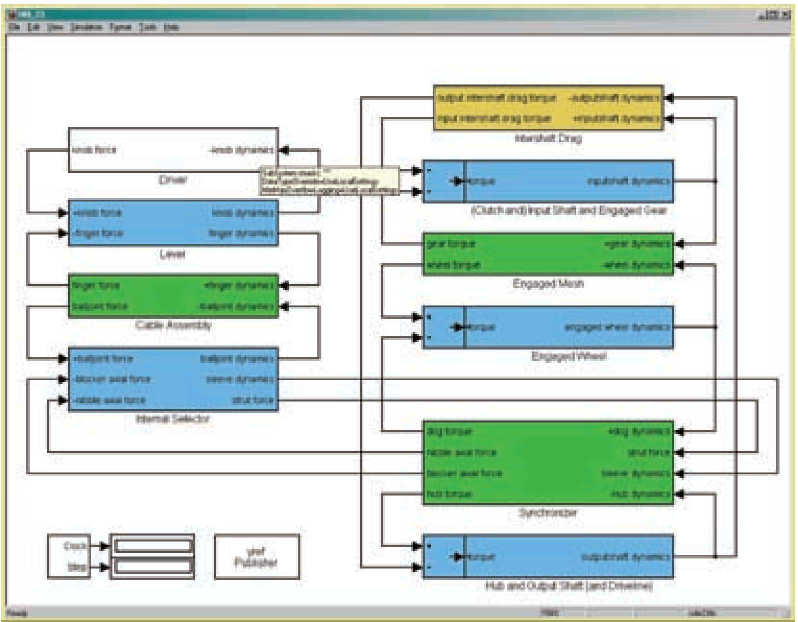

Figure 10: Shift comfort simulation model, root level

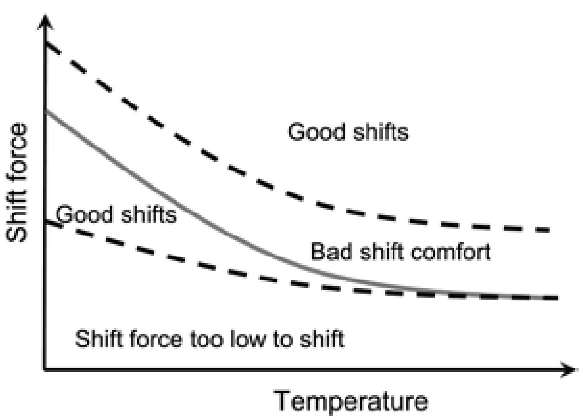

Figure 11: Shift comfort zones for oil temperature and shift force

dampers. Model properties are acquired from drawings, FE analysis and measurements. GM Powertrain has placed a lot of emphasis on sub-model correlation and has built rigs to measure the dynamics of a complete shift system, transmission drag torque, rubber element losses, etc. The strategy is to gain knowledge about the subsystem so that the number of parameters subject to estimation is minimized.

7.2 Correlation

When the model architecture is established and all sub-model correlations are achieved, the fully assembled model needs some final correlation. Since the model is large and contains many parameters, it is important to separate those that are well defined from those subject to engineering evaluation. The parameters which are not well defined are those the simulation engineer has to tune as for example friction coefficients. To ensure that the model shows a good overall correlation, the model is exercised and compared to a large variety of measured shifts. The virtual driver model is an important part of the simulation model. GM Powertrain has built a driver model that is able to mimic a driver's behavior from a measured gearshift to simplify the correlation.

7.3 Optimization

During optimization, the driver model used for model calibration is changed to a more general one which does not require input of measured data as boundary conditions for the analysis. It is important to identify and control parameter zones where bad shifts occur. A diagram of rating vs. shift force and oil temperature is used to illustrate this as it is shown in **Figure 11**.

The goal of optimization is to minimize problem areas where shifts with low ratings occur. This is achieved by improving the conditions for clean shifts, by moving the area to where it is less noticeable for the driver and by filtering the effect of a double bump and scratch.

8 Conclusion

A vital part of the shift comfort development process is to standardize the whole chain from an initial design via measurement to the analysis and simulation of a production feasible design. Recommendations of shift comfort improvement related design changes are based on several types of shifts in order to minimize sub optimization for one specific driver behavior. In the optimization of shift comfort plots illustrating good and bad shift area were used by GM Powertrain. The plot of shift comfort zones gives a good overview of the system performance.

The next challenge is to improve the simulation capability in early concept stage when having little to none measurements available. Knowledge of the system in the concept phase helps the engineers to set requirements on component level for a well tuned system with respect to shift comfort.

Reference

[1] Kirchner, E.: Leistungsübertragung in Fahrzeuggetrieben. Springer-Verlag, Berlin, 2007