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Torque, Judder, and Durability: Data-Driven Engineering of Clutch Friction Materials

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Clutch facings live at the intersection of driver feel, safety, and durability—and this book shows how to engineer them with data, not guesswork. Across nine studies, laboratory torque signals, finite element models, sub-scale benches, and statistical experiments are used to predict judder, burst resistance, and wear long before a vehicle hits the road. It is a practical blueprint for anyone who wants faster material development, fewer field surprises, and test methods that actually correlate with the car.

Contents

Chapter 1: Predicting Clutch Judder from Torque Signals

Judder is one of the most annoying and difficult clutch problems to diagnose, but the torque signal itself carries the answer. This chapter presents a data-driven learning system that reads dry-clutch torque signals, distinguishes among six friction materials, and predicts vehicle judder from a laboratory bench test.

Judder is the word the automotive industry uses for the longitudinal shudder you feel when a clutch engages. It is a comfort problem, but it is also a development problem: finding out whether a new friction material judders normally means putting it in a car and driving it.

? The problem

Earlier research had shown that judder can be explained through the behaviour of slip speed and temperature, both of which are captured inside the clutch torque signal. The signal carries the answer — the difficulty is extracting it in a way that is repeatable, cheap, and works before a facing ever reaches a vehicle.

? The approach

This work proposes a learning system built on a multivariate, data-driven analysis of torque signals. The experimental base was deliberately broad:

- a dry clutch system,
- a passenger car,
- a test bench,
- and six different organic facing materials.

Rather than model judder analytically, the method treats each torque signal as a high-dimensional observation and applies a regularized version of a standard linear classifier. The regularization matters — it is what keeps the model **stable** when there are far more signal samples than there are test runs.

? What came out of it

The resulting model is computationally efficient and highly accurate at discriminating torque signals from different facings, and it does so using only a handful of features. That compactness is the practical win: it means the classification can run quickly and be interpreted by an engineer.

The second result is the more useful one. By calculating the correlation pair-wise against a known *gold* material, it becomes possible to predict a judder problem in the vehicle from a standard bench test in the laboratory.

> The bench stops being a proxy measurement and becomes a prediction.

? Why it matters

Every judder evaluation that can be settled on a bench is a vehicle test that does not need to be run. Applied across a material development programme, that reduces both the time to develop a new friction material and the cost of qualifying it for judder-free performance.

? Full publication

Gregori, I. R. S.; Sanches, I.; Thomaz, C. E. — *Clutch Judder Classification and Prediction: A Multivariate Statistical Analysis Based on Torque Signals*. IEEE Transactions on Industrial Electronics, 64(5):4287–4295, November 2016. DOI: 10.1109/TIE.2016.2630666.

Read the full publication on ResearchGate

Chapter 2: A Gold Standard for Torque: Separating Clutch Facings by Judder Behaviour

> *Not all clutch facings are created equal, and multivariate statistics can prove it. Using real bench-test torque signals, this chapter separates facings by judder performance and manufacturing characteristics, and establishes a reference torque behaviour for material development.*

Driver comfort is a moving target, and judder — the low-frequency shudder during clutch engagement — is one of the things that has to be engineered out of it. Judder is genuinely complex, with contributions from engine excitation, misalignment, temperature and geometry. This work narrows the field deliberately and looks at one variable: the clutch facing.

? The problem

If several facings are run through the same bench test, an engineer can see that they behave differently. What is much harder is to say *how* they differ in a way that connects back to how the material was made, and to do it without falling back on subjective judgement of the torque trace.

? The approach

The study applies multivariate statistical analysis directly to the torque signal from a real bench test. Instead of reducing the signal to a single derived number, the whole signal is treated as the observation, and the statistical structure across facings is allowed to emerge from the data.

? What came out of it

The analysis separates the facings along two axes at once: their judder performance and their manufacturing characteristics. That dual separation is what makes the result actionable — a difference in judder behaviour can be traced back to something that was done differently on the production line.

Most importantly, the analysis establishes a *gold standard* behaviour for torque: a reference signature that a well-behaved facing produces. Having a target signature rather than a target score changes how a development programme is run.

> Having a target signature rather than a target score changes how a development programme is run.

? Why it matters

A gold standard torque behaviour gives friction material development a consistent reference to aim at, and a consistent way to understand judder rather than simply measure it. New formulations can be compared against the reference instead of against each other, which makes results comparable across programmes and over time.

?Compare new formulations against the reference signature, not against each other — that keeps results comparable across programmes and over time.

? Full publication

Gregori, I. R. S.; Thomaz, C. E.; Martins, C. G. — *Multivariate Judder Behavior Analysis of Dry Clutches Based on Torque Signal and Friction Material*, January 2015.

Read the full publication on ResearchGate

Chapter 3: Simulating Clutch Facing Burst Resistance with Finite Element Analysis

Burst resistance is a safety-critical property, yet testing every design variation experimentally is slow and expensive. This chapter applies finite element analysis to predict when a clutch facing bursts, with numerical results showing clear agreement with experimental burst tests.

Burst resistance is one of the few clutch facing characteristics where failure is immediate and total. If the facing bursts, the car does not drive off. That puts burst squarely in the safety, performance and lifetime bracket rather than the comfort bracket.

? The problem

Burst resistance has traditionally been established by spinning facings up until they fail. That works, but it tells you only the outcome. It does not show **where the stress concentrates**, how the material actually comes apart, or which design or process change would move the limit.

? The approach

The central question behind this paper is whether the burst of a facing material can be predicted using the finite element method. The objective goes beyond a pass/fail number: the aim is a better understanding of the stress fields inside the facing and of the failure micromechanisms that govern it.

? What came out of it

The numerical predictions showed very good agreement with experimental burst tests, with a clear correlation between simulated and measured behaviour. That correlation is what makes the model **trustworthy enough to use in decision making** rather than only for illustration.

With a validated model, the stress field becomes visible before anything is built, and the failure mechanism can be reasoned about directly.

?The validated correlation between simulation and experiment is what turns the model into a usable engineering tool rather than a purely academic exercise.

? Why it matters

Once burst can be simulated, three levers open up at once: the raw materials, the manufacturing process, and the geometric design of the facing can all be evaluated against maximum resistance without a physical prototype for every iteration. The conclusion of the work is that FEA is a valuable method for facing material development, not merely a verification step at the end of it.

? Full publication

Gregori, I. R. S.; da Silva, D. P.; Donato, G. — *Burst Resistance Simulation of Facing Material for Clutch Disc Based on Finite Element Analysis*. SAE Technical Papers, September 2014.

Read the full publication on ResearchGate

Chapter 4: Sub-Scale Judder Testing: Correlating a Bench Machine with the Vehicle

Full-vehicle judder testing is realistic but costly and slow. This chapter describes a methodology for classifying clutch facing judder sensitivity on a sub-scale bench test instead of a full vehicle, with preliminary results showing good correlation to the car.

Vehicle judder is defined as low-frequency, high-amplitude vibration during clutch engagement. Depending on intensity, it ranges from barely perceptible to genuinely uncomfortable to drive. The industry standard way to assess it is also the slowest one available.

? The problem

Today the judder test is performed in a car that is known to be sensitive to judder. The test itself is valid, but it is expensive in time: a complete clutch set — disc, clutch cover and flywheel — has to be assembled for every single test.

In a material development programme where dozens of formulations are screened, that assembly time **dominates the schedule**.

? The approach

This work develops a methodology to classify facing sensitivity to judder on a sub-scale bench test rather than in the vehicle. The goal is explicitly twofold: cut the time each test takes, and speed up friction material development as a whole by allowing more candidates to be screened.

Sub-scale means the test article is smaller than a production facing, which is what removes the full clutch-set assembly from the loop. The open question is whether a smaller sample, tested on a bench, still ranks materials the same way a car does.

?Correlation — not the raw numbers — is what determines whether a bench test can genuinely replace vehicle time.

? What came out of it

The preliminary results are described as **very promising**, because of a good correlation between the sub-scale tests and the vehicle. Correlation is the load-bearing word here — a bench test that produces numbers is easy, while a bench test that produces the *same ranking* as the car is the thing that actually replaces vehicle time.

? Why it matters

Screening on a sub-scale machine changes the economics of judder work. Candidates that would never have justified a vehicle test can be evaluated, and the vehicle is reserved for confirming the shortlist rather than discovering it.

? Full publication

Gregori, I. R. S.; Haertel Jr., W. — *Judder based on Sub Scale Test Machine Concerning Facing*. SAE Technical Papers, April 2013.

Read the full publication on ResearchGate

Chapter 5: Shrinking the Judder Test: A Sub-Scale Machine for Facing Sensitivity

> *Every test method starts with a proposal, and this chapter goes back to the original idea: move clutch facing judder classification off the vehicle and onto a sub-scale bench machine. The motivation was simple—test time and material development speed—and the result is a foundation for everything that follows.*

Judder shows up as low-frequency, high-amplitude vibration when the clutch engages, and at sufficient intensity it makes a car unpleasant to drive. Assessing it has always been a vehicle activity. This work asks whether it has to be.

? The problem

The judder test as practised is run in a car selected for being sensitive to judder. It takes a long time, and the reason is mechanical rather than procedural: each test requires assembling the complete clutch set — disc, clutch cover, flywheel. The measurement is quick; the preparation is not.

? The approach

The aim of this work is to develop a methodology for classifying facing sensitivity to judder in a sub-scale bench test. The motivation is stated as two distinct objectives rather than one: reducing test time, and speeding up facing material development.

They are related but not identical — the second is about how many ideas can be tried, not just how fast one can be checked.

? What came out of it

The preliminary results are promising, with a good correlation observed between the sub-scale tests and the vehicle. At this stage the claim is deliberately modest: the correlation exists and justifies continuing, which is what a first result from a new test method should establish.

? Why it matters

This paper marks the point where judder classification starts moving from a vehicle-bound evaluation to a laboratory one. The work was subsequently extended and reported again with further correlation data, but the framing set out here — sub-scale first, vehicle for confirmation — is what the later work builds on.

? Full publication

Gregori, I. R. S.; Domingues, A. — *Judder Based on Sub Scale Test Machine Concerning Facing*. SAE Technical Papers, October 2012.

Chapter 6: Classifying Clutch Facing Judder Sensitivity: Simulation Plus Vehicle Validation

Simulation saves time, but only if it is validated against reality. This chapter presents a two-part methodology for characterising facing judder sensitivity: numerical simulation of the judder bench test, validated against an experimental judder test in a passenger car.

Vehicle judder — low-frequency, high-amplitude vibration during clutch engagement — can make driving uncomfortable when it is severe enough. A bench test exists specifically to measure the judder sensitivity of the friction material used on clutch discs, which means the measurement problem is solved. The characterization problem is not.

? The problem

Having a bench test is not the same as having a methodology. To classify facings by judder sensitivity you need to know what the bench test predicts, how reliable that prediction is, and how it maps to what a driver experiences in a car.

? The approach

The study was divided into two parts. In the first, an alternative was developed by running a numerical simulation of the judder bench test, using three different facing materials as the basis. Simulating the bench rather than running it is what saves the test time.

In the second part, an experimental judder test was carried out in a passenger car. This served two purposes at once: to validate the efficiency of the numerical simulation, and to independently classify the judder sensitivity of the same three materials.

? What came out of it

> The pairing is the point. The vehicle test is not merely a demonstration — it is the reference that tells you whether the simulation is worth trusting, and the simulation is what makes the classification cheap enough to apply broadly once trust is established.

? Why it matters

This methodology sits upstream of the later sub-scale bench work. It establishes the validation discipline that the subsequent papers depend on: a laboratory method only earns the right to replace a vehicle test after the vehicle test has confirmed it.

? Full publication

Gregori, I. R. S. — *Methodology to Determine the Clutch Facing Sensitivity Regarding Judder in the Vehicle.*

SAE Technical Papers, October 2010. Full text available.

Read the full publication on ResearchGate

Chapter 7: Finding the Hidden Process Variables Behind Clutch Facing Burst Resistance

Burst resistance varies not only by material but by how that material is processed. This chapter uses multivariate exploratory analysis of eight process variables to identify two that correlate with burst resistance—one positively, one negatively—and process changes based on that finding raised both burst resistance and reliability.

A specific clutch facing part number carried an unusually high customer specification for burst resistance. Meeting it consistently, rather than on average, meant improving the reliability of the characteristic itself — and that meant understanding what in the manufacturing process was driving it.

? The problem

Burst resistance is an outcome of many process variables acting together. Looking at them one at a time tends to hide the relationships, and treating the process data before analysis risks removing exactly the structure you are trying to find.

? The approach

The decision was to use multivariable analysis tools — tree clustering diagram analysis and principal component analysis — applied to data taken directly from the process, without special treatment. Exploring the raw process data is what allows relationships to surface on their own rather than being assumed in advance.

Eight process variables were investigated.

? What came out of it

Two of the eight variables showed a correlation with burst resistance. The interesting detail was the direction: one variable correlated positively with the burst test results and the other negatively. That opposition was hidden inside the process and would have been very difficult to see in a conventional correlation study, since the two effects partially mask each other when variables are examined in isolation.

Knowing the sign of each relationship is what made the information usable for decisions. After changes were made to the process on that basis, burst resistance increased — and so did reliability, which was the actual customer requirement.

? Why it matters

This is multivariate analysis used as an engineering instrument rather than a reporting technique. The result was not a better description of the process but a specific, directional change to it, validated by the characteristic the customer was measuring.

? Full publication

Gregori, I. R. S.; Damatto, R.; Haertel, W. — *Multivariate Exploratory Techniques Helping to Increase the Reliability of Facing Clutch Material Burst Resistance*. SAE Technical Papers, April 2008.

Read the full publication on ResearchGate

Chapter 8: Linking Bench Wear to Vehicle Mileage with DOE and Weibull Analysis

Bench wear results are useful only if they translate into field durability. This chapter links bench wear to vehicle mileage using design of experiments and Weibull analysis, making it possible to estimate field durability from bench results.

Friction facing durability in the field varies a great deal, and in most cases very little is known about the conditions the vehicle actually operated under.

Two customers can wear out the same facing at very different rates, and without the operating history there is no way to tell whether that reflects the material or the use.

? The problem

Field data is plentiful but uncontrolled. Bench data is controlled but does not obviously translate to mileage.

Bridging the two requires a test procedure designed to span the range of conditions a vehicle is subjected to, plus a statistical framework strong enough to handle the scatter that remains.

? The approach

A test procedure was developed capable of containing the different operating conditions of a vehicle. Statistical applications were then used on top of it: design of experiments (DOE) to plan the tests and derive equations from the results, and Weibull curves for the reliability analysis of wear life.

?DOE is what keeps the test matrix efficient — the conditions are chosen so that the effects of **energy** and **working temperature** can be separated rather than confounded.

? What came out of it

A correlation was determined between wear results on the bench and vehicle mileage. With that correlation in hand, the durability of a friction facing on a vehicle can be estimated from bench testing alone.

A second outcome was knowledge about how the material behaves relative to energy and working temperature — not just how long it lasts, but what drives how long it lasts.

? Why it matters

Estimating field durability from a bench removes the longest feedback loop in friction material development.

> It also makes durability claims defensible, because they rest on a documented correlation and a Weibull reliability model rather than on accumulated field impressions.

? Full publication

Gregori, I. R. S.; Zanotto, P.; Haertel, W. — *Definition of the Relationship Between Clutch Facing on Vehicle and Bench Testing Using Reliability and DOE*. SAE Technical Paper 2005-01-1766, April 2005.

Read the full publication on ResearchGate

Chapter 9: Building a Test Procedure for Friction Facing Durability

Durability testing needs to reflect the full range of real-world operating conditions, not just a single worst case. This chapter presents the original bench test procedure built to contain that full range, so that friction facing durability can be studied without depending on uncontrolled field data.

Durability results for friction facings in field applications vary widely. The usual explanation is the material, but the honest answer is that nobody knows: in most cases there is very little information about the conditions under which the vehicle was operated.

? The problem

Without operating history, field wear data cannot be interpreted. A facing that wore quickly might have been driven hard, driven hot, or simply driven in traffic. Comparing two materials on field returns therefore compares usage patterns as much as it compares materials.

?Field wear data without operating history is not comparable between materials — it reflects usage as much as the facing itself.

? The approach

The response was to develop a test procedure capable of containing all the different operating conditions of a vehicle within a controlled bench test. Rather than sampling real-world usage after the fact, the range of usage is built into the test matrix from the start.

Reliability methods and design of experiments provide the structure: DOE to lay out the conditions efficiently, and reliability analysis to handle the scatter that remains in wear data even under controlled conditions.

- ? DOE to lay out the operating conditions efficiently
- ? Reliability analysis to handle the scatter that remains in wear data

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? What came out of it

The procedure establishes a controlled basis for studying facing durability — one where the operating conditions are known by construction rather than reconstructed by guesswork.

? Why it matters

This is the groundwork for correlating bench wear with vehicle mileage. The correlation and the **Weibull reliability** treatment were developed and reported in the extended version of this work, but they depend entirely on having a test procedure that spans the conditions a vehicle actually sees.

> Known conditions by construction, not by guesswork — that is what makes bench-to-vehicle correlation possible.

? Full publication

Gregori, I. R. S. — *Definition of the Relationship Between Clutch Facing on Vehicle and Bench Testing Using Reliability and DOE*. SAE Technical Papers, November 2004.

Read the full publication on ResearchGate