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# FFB Mathematical Formulas (v0.6.2)

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## ⚠ API Source of Truth

All telemetry data units and field names are defined in `src/lmu_sm_interface/InternalsPlugin.hpp`.

Critical: `mSteeringShaftTorque` is in Newton-meters (Nm).

The final output sent to the DirectInput driver is a normalized value between -1.0 and 1.0.

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## 1. The Master Formula

$$F_{\text{final}} = \text{Clamp}(\text{Normalize}(F_{\text{total}}) \times K_{\text{gain}}, -1.0, 1.0)$$

where normalization divides by `m_max_torque_ref` (with a floor of 1.0 Nm).

The total force is a summation of base physics, seat-of-pants effects, and dynamic vibrations:

$$F_{\text{total}} = (F_{\text{base}} + F_{\text{sop}} + F_{\text{vib-lock}} + F_{\text{vib-spin}} + F_{\text{vib-slide}} + F_{\text{vib-road}} + F_{\text{vib-bottom}} + F_{\text{gyro}} + F_{\text{abs}})$$

*Note: Traction Loss ( $F_{\text{vib-spin}}$ ) also applies a multiplicative reduction to the total force (see Section E.3).*

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## 2. Signal Scalers (Decoupling)

To ensure consistent feel across different wheels (e.g. G29 vs Simucube), effect intensities are automatically scaled based on the user's `Max Torque Ref`.

- Reference Torque: 20.0 Nm.
  - Decoupling Scale: `K_decouple = m_max_torque_ref / 20.0`.
  - *Note: This ensures that 10% road texture feels the same physical intensity regardless of wheel strength.*
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## 3. Component Breakdown

### A. Load Factors (Safe Caps)

Texture and vibration effects are scaled by normalized tire load (`Load / 4000N`) to simulate connection with the road. Safe caps prevent force spikes during glitches or aero anomalies.

#### 1. Texture Load Factor (Road/Slide):

- $F_{\text{load-texture}} = \text{Clamp}(\text{Load}/4000.0, 0.0, m_{\text{texture-load-cap}})$
- **Max Cap:** 2.0.

## 2. Brake Load Factor (Lockup):

- $F_{\text{load-brake}} = \text{Clamp}(\text{Load}/4000.0, 0.0, m_{\text{brake-load-cap}})$
- **Max Cap:** 3.0 (Allows stronger vibration under high-downforce braking).

## B. Base Force Components

### 1. Base Force Calculation ( $F_{\text{base}}$ )

Modulates the raw steering torque (`mSteeringShaftTorque`) based on front tire grip.

$$F_{\text{base}} = \text{BaseInput} \times K_{\text{shaft-smooth}} \times K_{\text{shaft-gain}} \times (1.0 - (\text{GripLoss} \times K_{\text{understeer}}))$$

- **Operation Modes ( $m_{\text{base-force-mode}}$ ):**

- **Mode 0 (Native):**  $\text{BaseInput} = T_{\text{shaft}}$ . (Default precision mode).
- **Mode 1 (Synthetic):**  $\text{BaseInput} = \text{Sign}(T_{\text{shaft}}) \times m_{\text{max-torque-ref}}$ .
  - Used for debugging direction only.
  - **Deadzone:** Applied if  $|T_{\text{shaft}}| < 0.5\text{Nm}$  to prevent center oscillation.

- **Mode 2 (Muted):**  $\text{BaseInput} = 0.0$ .

- **Steering Shaft Smoothing:** Time-Corrected LPF ( $\tau = m_{\text{shaft-smooth}}$ ) applied to raw torque.

### 2. Grip Estimation & Fallbacks

If telemetry grip (`mGripFract`) is missing or invalid (< 0.0001), the engine approximates it:

- **Combined Friction Circle:**

- $\text{Metric}_{\text{lat}} = |\alpha|/\text{OptAlpha}$  (Lateral Slip Angle)
- $\text{Metric}_{\text{long}} = |\kappa|/\text{OptRatio}$  (Longitudinal Slip Ratio)
- $\text{Combined} = \sqrt{\text{Metric}_{\text{lat}}^2 + \text{Metric}_{\text{long}}^2}$
- $\text{ApproxGrip} = (1.0 \text{ if } \text{Combined} < 1.0 \text{ else } 1.0 / (1.0 + (\text{Combined} - 1.0) \times 2.0))$

- **Safety Clamp:** Approx Grip is usually clamped to min 0.2 to prevent total loss of force.

### 3. Kinematic Load Reconstruction

If `mSuspForce` is missing (encrypted content), tire load is estimated from chassis physics:

- $F_z = F_{\text{static}} + F_{\text{aero}} + F_{\text{long-transfer}} + F_{\text{lat-transfer}}$

- **Static:** Mass (1100kg default) distributed by Weight Bias (55% Rear).
- **Aero:**  $2.0 \times \text{Velocity}^2$ .
- **Transfer:**
  - Longitudinal:  $(\text{Accel}_Z / 9.81) \times 2000.0$ .
  - Lateral:  $(\text{Accel}_X / 9.81) \times 2000.0 \times 0.6$  (Roll Stiffness).

## C. Seat of Pants (SoP) & Oversteer

### 1. Lateral G Force ( $F_{\text{sop-base}}$ ):

- **Input:** `mLocalAccel.x` (Clamped to +/- 5.0 G).
- **Smoothing:** Time-Corrected LPF ( $\tau \approx 0.0225 - 0.1$ s mapped from scalar).
- **Formula:**  $G_{\text{smooth}} \times K_{\text{sop}} \times K_{\text{sop-scale}} \times K_{\text{decouple}}$ .

### 2. Yaw Acceleration ("The Kick"):

- **Input:** `mLocalRotAccel.y` (rad/s<sup>2</sup>).
- **Conditioning:**
  - **Low Speed Cutoff:** 0.0 if Speed < 5.0 m/s.
  - **Noise Gate:** 0.0 if  $|\text{Accel}| < 0.2$  rad/s<sup>2</sup>.
- **Formula:**  $-\text{YawAccel}_{\text{smooth}} \times K_{\text{yaw}} \times 5.0 \text{Nm} \times K_{\text{decouple}}$ .
- **Note:** Negative sign provides counter-steering torque.

### 3. Rear Aligning Torque ( $T_{\text{rear}}$ ):

- **Workaround:** Uses `RearSlipAngle * RearLoad * Stiffness(15.0)` to estimate lateral force.
- **Formula:**  $-F_{\text{lat-rear}} \times 0.001 \times K_{\text{rear}} \times K_{\text{decouple}}$ .
- **Clamp:** Lateral Force clamped to +/- 6000N.

## D. Braking & Lockup (Advanced)

### 1. Progressive Lockup ( $F_{\text{vib-lock}}$ )

- **Predictive Logic (v0.6.0):** Triggers early if `WheelDecel > CarDecel * 2.0` (Wheel stopping faster than car).
- **Bump Rejection:** Logic disabled if `SuspVelocity > m_lockup_bump_reject` (e.g. 1.0 m/s).
- **Severity:** Severity =  $\text{pow}(\text{NormSlip}, m_{\text{lockup-gamma}})$  (Quadratic).
- **Logic:**

- **Axle Diff:** Rear lockups use 0.3x Frequency and 1.5x Amplitude.
- **Pressure Scaling:** Scales with Brake Pressure (Bar). Fallback to 0.5 if engine braking (Pressure < 0.1 bar).
- **Oscillator:** `sin(Phase)` (Wrapped via `fmod`).

## 2. ABS Pulse ( $F_{abs}$ )

- **Trigger:** Brake > 50% AND Pressure Modulation Rate > 2.0 bar/s.
- **Formula:** `sin(20Hz) * K_abs * 2.0Nm`.

## E. Dynamic Textures & Vibrations

### 1. Slide Texture (Scrubbing)

- **Scope:** `Max(FrontSlipVel, RearSlipVel)` (Worst axle dominates).
- **Frequency:**  $10\text{Hz} + (\text{SlipVel} \times 5.0)$ . Cap 250Hz.
- **Amplitude:**  $\text{Sawtooth}(\phi) \times K_{slide} \times 1.5\text{Nm} \times F_{load-texture} \times (1.0 - \text{Grip}) \times K_{decouple}$ .
- **Note:** Work-based scaling `(1.0 - Grip)` ensures vibration only occurs during actual scrubbing.

### 2. Road Texture (Bumps)

- **Main Input:** Delta of `mVerticalTireDeflection`.
- **Formula:** `(DeltaL + DeltaR) * 50.0 * K_road * F_load_texture * Scale`.
- **Scrub Drag (Fade-In):**
  - Adds constant resistance when sliding laterally.
  - **Fade-In:** Linear scale 0% to 100% between 0.0 m/s and 0.5 m/s lateral velocity.
  - **Formula:** `(SideVel > 0 ? -1 : 1) * K_drag * 5.0Nm * Fade * Scale`.

### 3. Traction Loss (Wheel Spin)

- **Trigger:** Throttle > 5% and SlipRatio > 0.2 (20%).
- **Torque Drop:** The *Total Output Force* is reduced to simulate "floating" front tires.
  - `F_total *= (1.0 - (Severity * K_spin * 0.6))`
- **Vibration:**
  - **Frequency:**  $10\text{Hz} + (\text{SlipSpeed} \times 2.5)$ . Cap 80Hz.
  - **Formula:**  $\sin(\phi) \times \text{Severity} \times K_{spin} \times 2.5\text{Nm} \times K_{decouple}$ .

### 4. Suspension Bottoming

- Triggers:
  - Method A: `RideHeight < 2mm`.
  - Method B: `SuspForceRate > 100,000 N/s`.
  - Legacy: `TireLoad > 8000.0 N`.
- Formula:  $\sin(50\text{Hz}) * K_{\text{bottom}} * 1.0\text{Nm}$ .

## F. Post-Processing & Filters

### 1. Signal Filtering

- Notch Filters:
  - Dynamic:  $F_{\text{req}} = \text{Speed}/\text{Circumference}$ . Uses Biquad.
  - Static: Fixed frequency (e.g. 50Hz) Biquad.
- Frequency Estimator: Tracks zero-crossings of `mSteeringShaftTorque` (AC coupled).

### 2. Gyroscopic Damping ( $F_{\text{gyro}}$ )

- Formula:  $-\text{SteerVel}_{\text{smooth}} \times K_{\text{gyro}} \times (\text{Speed}/10.0) \times 1.0\text{Nm} \times K_{\text{decouple}}$ .
- Smoothing: Time-Corrected LPF.

### 3. Min Force (Friction Cancellation)

Applied at the very end of the pipeline to `F_norm` (before clipping).

- Logic: If  $|F| > 0.0001$  AND  $|F| < K_{\text{min-force}}$ :
  - $F_{\text{final}} = \text{Sign}(F) \times K_{\text{min-force}}$ .
- Purpose: Ensures small forces are always strong enough to overcome the physical friction/deadzone of gear/belt wheels.

## 6. Legend: Physics Constants (Implementation Detail)

Constant Name	Value	Description
<code>BASE_NM_LOCKUP</code>	4.0 Nm	Reference intensity for lockup vibration
<code>BASE_NM_SPIN</code>	2.5 Nm	Reference intensity for wheel spin
<code>BASE_NM_ROAD</code>	2.5 Nm	Reference intensity for road bumps
<code>REAR_STIFFNESS</code>	15.0	N/(rad·N) - Estimated rear tire cornering stiffness

Constant Name	Value	Description
WEIGHT_TRANSFER_SCALE	2000.0	N/G - Kinematic load transfer scaler
UNSPRUNG_MASS	300.0 N	Per-corner static unsprung weight estimate
BOTTOMING_LOAD	8000.0 N	Load required to trigger legacy bottoming
BOTTOMING_RATE	100kN/s	Suspension force rate for impact bottoming
MIN_SLIP_VEL	0.5 m/s	Low speed threshold for slip angle calculation