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FFB Mathematical Formulas (v0.6.2)

⚠ 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.

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).

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. (Updated from legacy 4000 unitless reference).
 - **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.

1. Texture Load Factor (Road/Slide):

- **Input:** $\text{AvgLoad} = (\text{FL.Load} + \text{FR.Load}) / 2.0$.
- **Robustness Check:** Uses a hysteresis counter; if $\text{AvgLoad} < 1.0$ while moving, it falls back to Kinematic Load or Approximate Load logic.
- $F_{\text{load-texture}} = \text{Clamp}(\text{AvgLoad}/4000.0, 0.0, m_{\text{texture-load-cap}})$
- **Max Cap:** 2.0.

2. Brake Load Factor (Lockup):

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

B. Base Force Components

1. Base Force Calculation (F_{base})

Modulates the raw steering torque ($m_{\text{SteeringShaftTorque}}$) 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 ($m_{\text{GripFract}}$) is missing or invalid (< 0.0001), the engine approximates it:

- **Low Speed Trap:** If $\text{CarSpeed} < 5.0 \text{ m/s}$, Grip is forced to 1.0 (Prevents singularities at parking speeds).
- **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 ($\tau \approx 0.0225 - 0.1\text{s}$ mapped from scalar).
- **Formula:** $G_{\text{smooth}} \times K_{\text{sop}} \times K_{\text{sop-scale}} \times K_{\text{decouple}}$.

2. Lateral G Boost (F_{boost}):

- Amplifies the SoP force when the car is oversteering (Front Grip > Rear Grip).
- **Condition:** `if (FrontGrip > RearGrip)`
- **Formula:** `SoP_Total *= (1.0 + ((FrontGrip - RearGrip) * K_oversteer_boost * 2.0))`

3. Yaw Acceleration ("The Kick"):

- **Input:** `mLocalRotAccel.y` (rad/s²).
- **Conditioning:**
 - **Low Speed Cutoff:** 0.0 if Speed < 5.0 m/s.
 - **Noise Gate:** 0.0 if $|\text{Accel}| < 0.2 \text{ rad/s}^2$.
- **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.

4. Rear Aligning Torque (T_{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:** $\text{Severity} = \text{pow}(\text{NormSlip}, m_{\text{lockup-gamma}})$ (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:** $\text{Sawtooth}(\phi) \times K_{\text{slide}} \times 1.5\text{Nm} \times F_{\text{load-texture}} \times (1.0 - \text{Grip}) \times K_{\text{decouple}}$.
- **Note:** Work-based scaling `(1.0 - Grip)` ensures vibration only occurs during actual scrubbing.

2. Road Texture (Bumps)

- **Main Input:** Delta of `mVerticalTireDeflection`.
- **Safety Clamp:** Delta is clamped to +/- 0.01m per frame to prevent physics explosions on teleport or restart.
- **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:** $(\text{SideVel} > 0 ? -1 : 1) * K_{\text{drag}} * 5.0\text{Nm} * \text{Fade} * \text{Scale}$.

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.
 - $F_{\text{total}} *= (1.0 - (\text{Severity} * K_{\text{spin}} * 0.6))$
- **Vibration:**
 - **Frequency:** $10\text{Hz} + (\text{SlipSpeed} \times 2.5)$. Cap 80Hz.
 - **Formula:** $\sin(\phi) \times \text{Severity} \times K_{\text{spin}} \times 2.5\text{Nm} \times K_{\text{decouple}}$.

4. Suspension Bottoming

- **Triggers:**
 - Method A: $\text{RideHeight} < 2\text{mm}$.
 - Method B: $\text{SuspForceRate} > 100,000 \text{ N/s}$.
 - Legacy: $\text{TireLoad} > 8000.0 \text{ N}$.
- **Formula:** $\sin(50\text{Hz}) * K_{\text{bottom}} * 1.0\text{Nm}$. (Fixed sinusoidal crunch).
- **Legacy Intensity:** $\sqrt{\text{ExcessLoad}} \times 0.05$. (Retained for high-load bottoming).

F. Post-Processing & Filters

1. Signal Filtering

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

2. Gyroscopic Damping (F_{gyro})

- **Input Derivation:**
 - $\text{SteerAngle} = \text{UnfilteredInput} \times (\text{RangeInRadians} / 2.0)$
 - $\text{SteerVel} = (\text{Angle}_{\text{current}} - \text{Angle}_{\text{prev}}) / dt$

- **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. Time-Corrected LPF (Algorithm)

Standard exponential smoothing filter used for Slip Angle, Gyro, SoP, and Shaft Torque.

- **Formula:** $State+ = \alpha \times (Input - State)$
- **Alpha Calculation:** $\alpha = dt/(\tau + dt)$
 - dt : Delta Time (e.g., 0.0025s)
 - τ (Tau): Time Constant (User Configurable, or derived from smoothness).

4. 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.

7. Telemetry Variable Mapping

Math Symbol	API Variable	Description
T_{shaft}	<code>mSteeringShaftTorque</code>	Raw steering torque (Nm)
Load	<code>mTireLoad</code>	Vertical load on tire (N)
GripFract	<code>mGripFract</code>	Tire grip scaler (0.0-1.0)
Accel_x	<code>mLocalAccel.x</code>	Lateral acceleration (m/s ²)
Accel_z	<code>mLocalAccel.z</code>	Longitudinal acceleration (m/s ²)
YawAccel	<code>mLocalRotAccel.y</code>	Rotational acceleration (rad/s ²)
Vel_z	<code>mLocalVel.z</code>	Car speed (m/s)
$\text{SlipVel}_{\text{lat}}$	<code>mLateralPatchVel</code>	Scrubbing velocity (m/s)
SuspForce	<code>mSuspForce</code>	Suspension force (N)
$\text{Pedal}_{\text{brake}}$	<code>mUnfilteredBrake</code>	Raw brake input (0.0-1.0)

8. Legend: Physics Constants (Implementation Detail)

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