Scenario 3A — Steep Uphill Simulation

Metamorphic Relation Type: Composite (C), composed of Multiplicative (M) and Additive (A) relations

Composite dynamic behavior under causal constraints

Description

This scenario evaluates the system's behavior under a composite dynamic regime characterized by moderate constant speed and persistent positive acceleration. The test case simulates a steep uphill driving condition, in which the system is continuously subjected to increased load demand.

In this scenario, the metamorphic transformation is applied from the beginning of the trajectory (sample index 0) and remains active throughout the entire sequence. Consequently, all samples are modified to reflect a sustained uphill driving condition, with constant speed and positive acceleration.

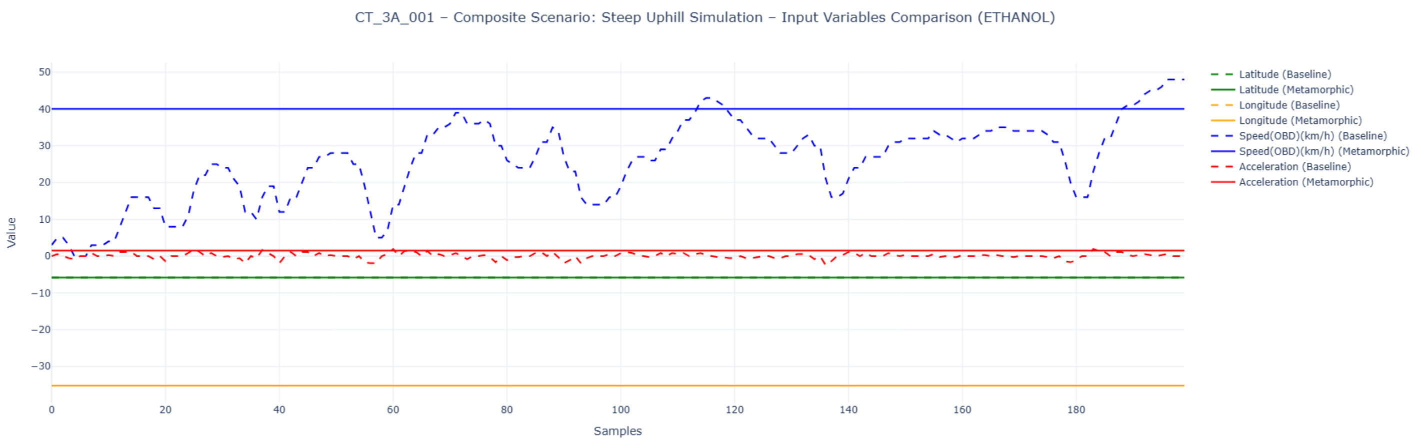
Unlike isolated transformations applied in previous levels, this scenario combines multiple kinematic conditions into a coherent temporal pattern affecting the full duration of the signal.

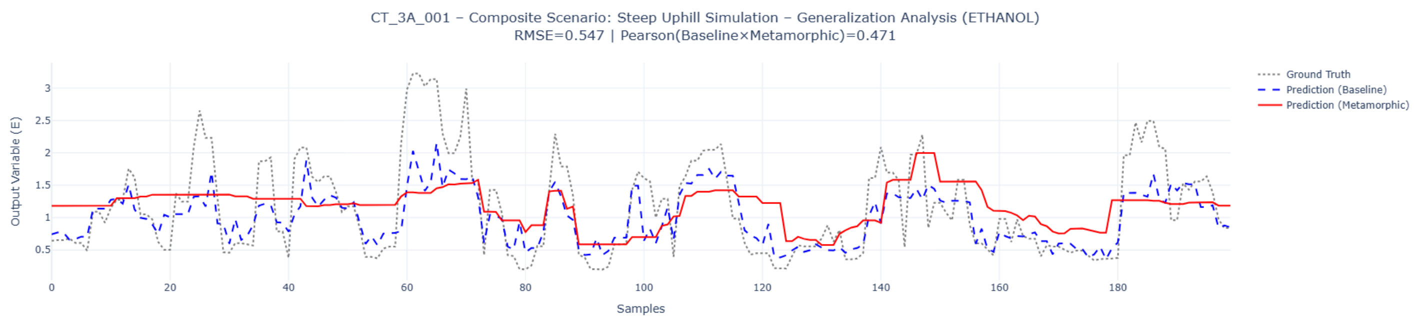
The objective is to observe whether the system produces a stable and causally consistent output under sustained positive acceleration, without execution interruption or erratic behavior.

Test Cases

CT_3A_001 — Composite Scenario (Steep Uphill Simulation) — Ethanol

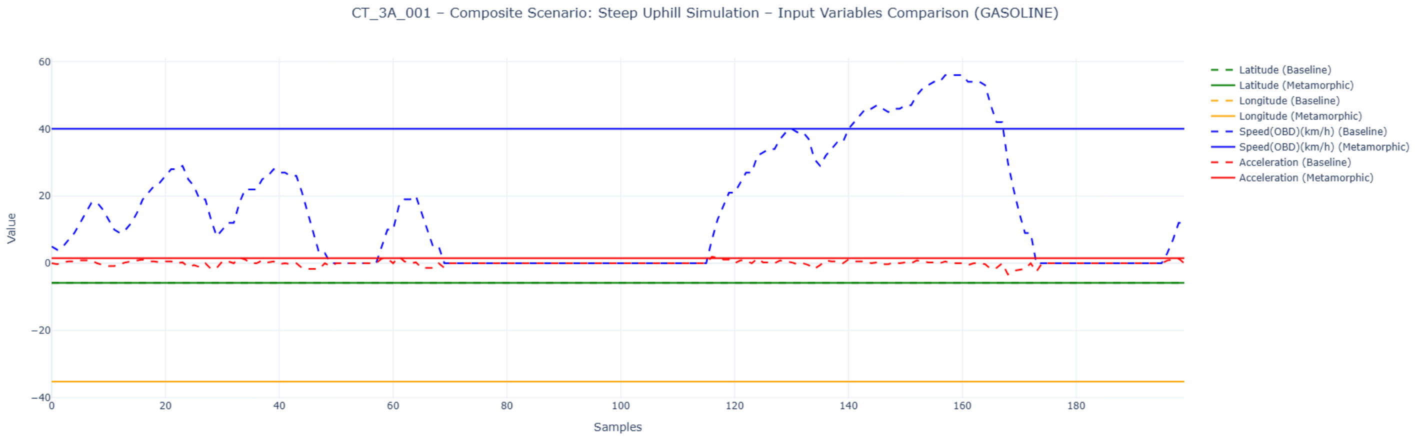
- **RMSE (Baseline × Metamorphic Prediction):** 0.5474
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.471
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.373

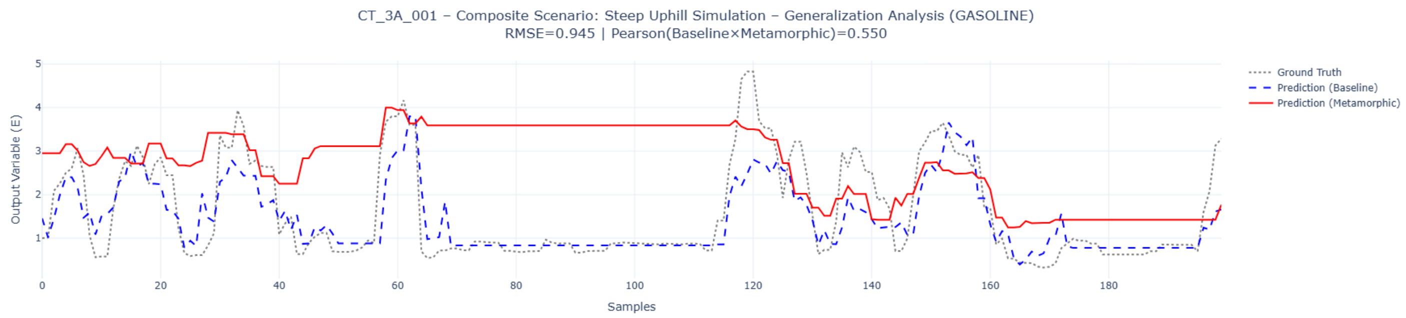




CT_3A_001 — Composite Scenario (Steep Uphill Simulation) — Gasoline

- **RMSE (Baseline × Metamorphic Prediction):** 0.9451
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.550
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.412





Scenario 3B — Downhill Inertia Simulation

Metamorphic Relation Type: Composite (C), composed of Multiplicative (M) and Inversive (IV) relations

Composite dynamic behavior dominated by inertial effects

Description

This scenario evaluates the system's behavior under a composite dynamic regime characterized by high speed and mild negative acceleration, representing a downhill driving condition dominated by inertia.

In this scenario, the metamorphic transformation is applied from the beginning of the trajectory (sample index 0) and remains active throughout the entire sequence. Consequently, all samples are modified to reflect a sustained inertial condition characterized by constant high speed and negative acceleration.

From a metamorphic testing perspective, this composite relation combines a Multiplicative component, associated with the scaling of acceleration toward negative values, and an Inversive component, associated with the change in acceleration direction relative to propulsion-driven motion.

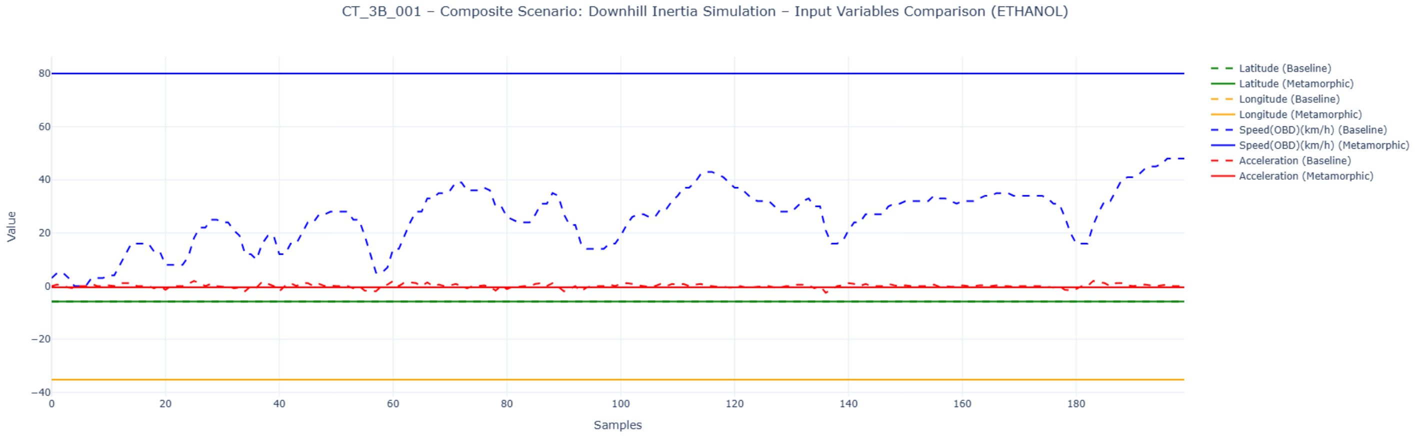
The test case models a situation in which the vehicle progressively loses speed without active braking, relying primarily on inertial and gravitational effects. This configuration combines kinematic variables in a semantically coherent manner, reflecting a realistic operational pattern affecting the full duration of the signal.

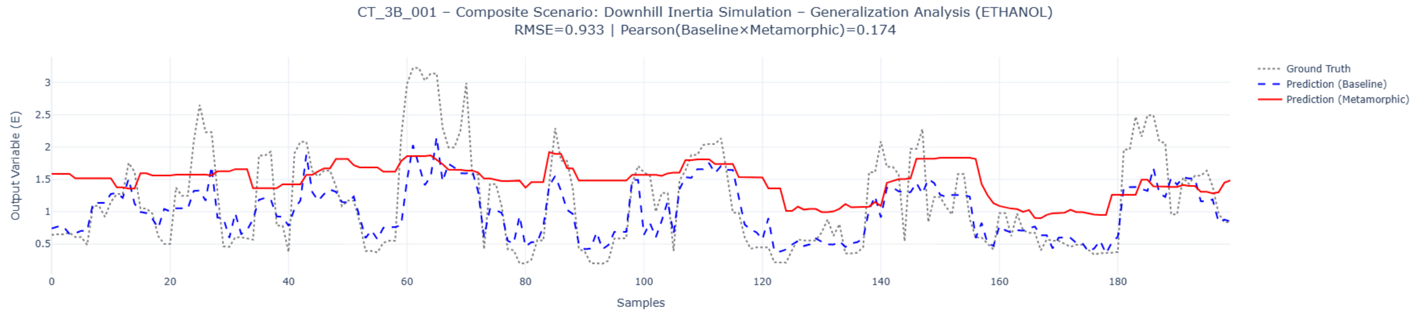
The objective is to assess whether the system maintains causal consistency and execution stability when subjected to gradual deceleration driven by inertia rather than abrupt control actions.

Test Cases

CT_3B_001 — Composite Scenario (Downhill Inertia Simulation) — Ethanol

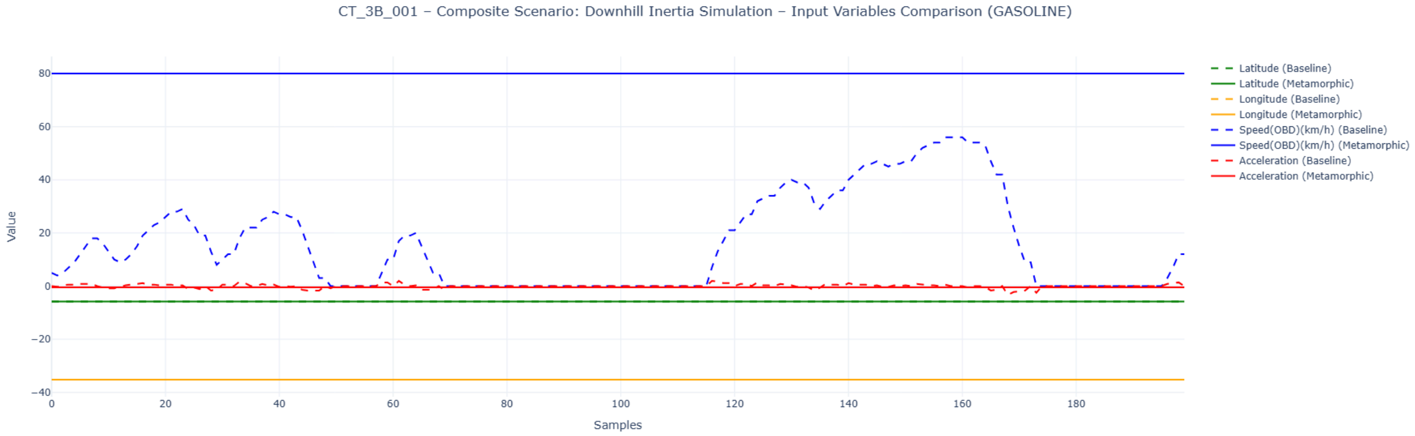
- **RMSE (Baseline × Metamorphic Prediction):** 0.9333
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.174
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.140

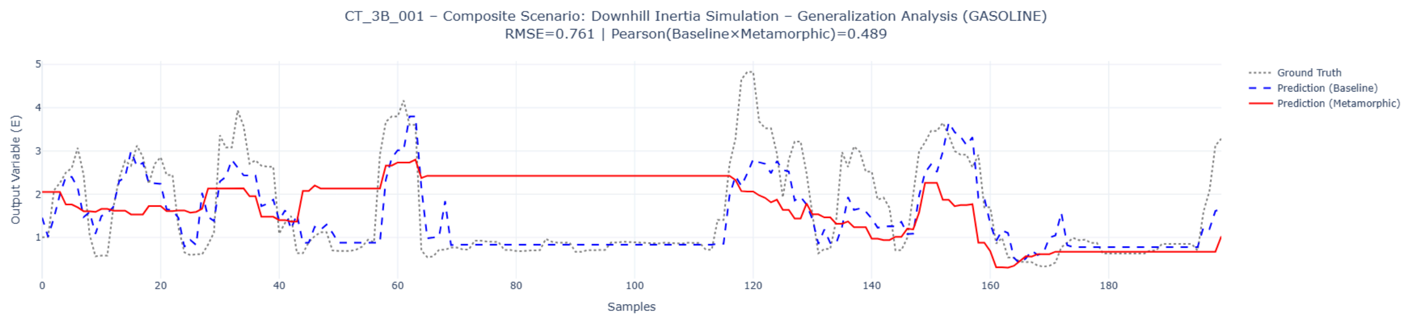




CT_3B_001 — Composite Scenario (Downhill Inertia Simulation) — Gasoline

- **RMSE (Baseline × Metamorphic Prediction):** 0.7613
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.489
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.362





Scenario 3C — Hard Braking with Fuel Cut-Off

Metamorphic Relation Type: Composite (C), composed of Inversive (IV), Multiplicative (M), and Boundary (B) relations

Composite critical and transient dynamic behavior

Description

This scenario evaluates the system’s behavior during a critical transient event characterized by intense negative acceleration and rapid reduction of speed to zero, representing a hard braking condition with potential fuel cut-off.

In this scenario, the metamorphic transformation is introduced at sample index 120 and remains active until the end of the sequence. From this point onward, vehicle speed is progressively reduced until reaching zero, after which both speed and acceleration remain at their minimum boundary values, representing a stationary condition.

From a metamorphic testing perspective, this composite relation combines an Inversive component, associated with the reversal of acceleration direction during braking, a Multiplicative component, associated with the progressive reduction of speed and acceleration magnitudes, and a Boundary component, associated with the enforcement of the physical lower limit where motion variables reach and remain at zero.

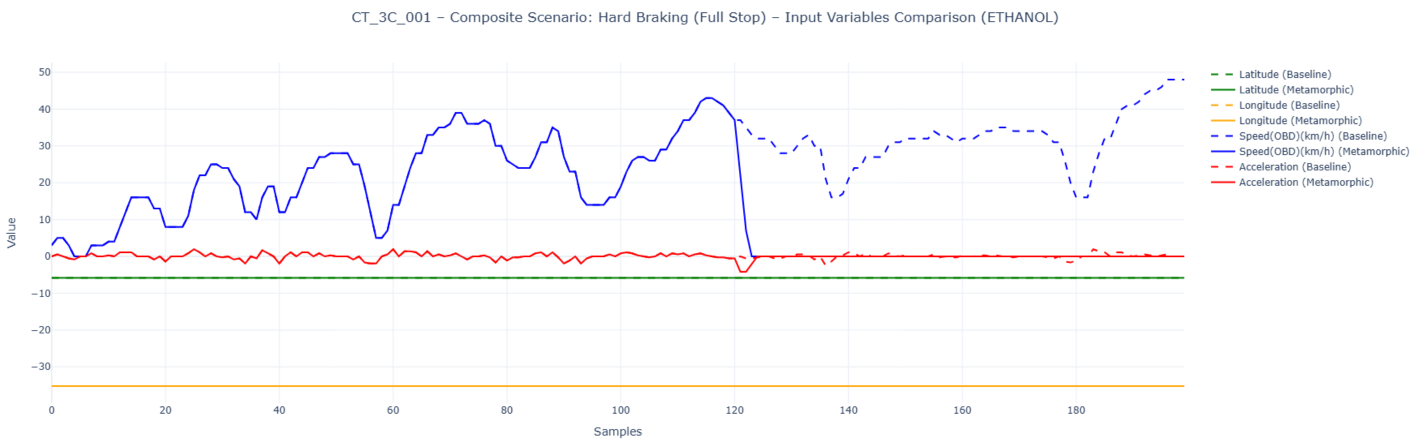
The test case models an abrupt deceleration pattern in which vehicle motion is rapidly interrupted. Such conditions impose strong dynamic discontinuities on the input signals and are expected to induce significant changes in the system output.

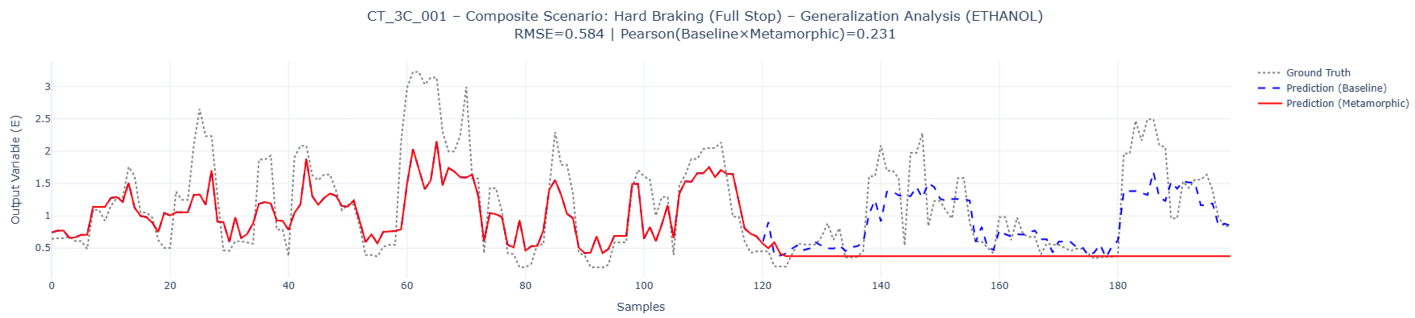
The objective is to assess whether the system preserves execution stability, causal coherence, and controlled output behavior when subjected to sudden braking events.

Test Cases

CT_3C_001 — Composite Scenario (Hard Braking / Fuel Cut-Off) — Ethanol

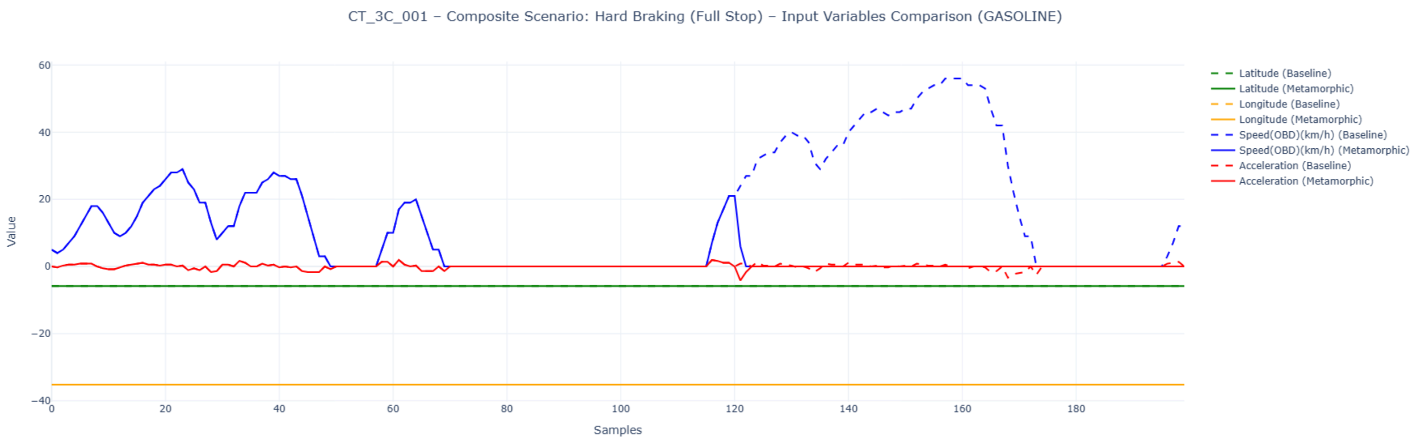
- **RMSE (Baseline × Metamorphic Prediction):** 0.5838
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.231
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.203

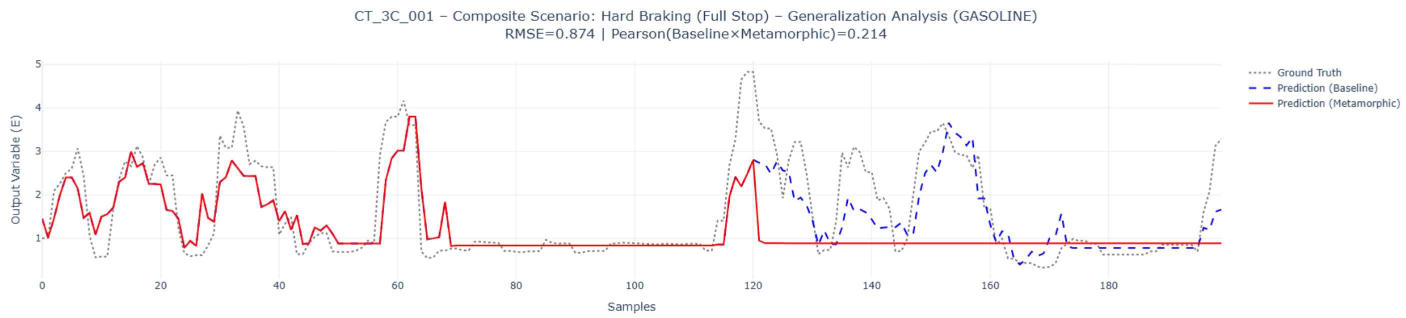




CT_3C_001 — Composite Scenario (Hard Braking / Fuel Cut-Off) — Gasoline

- **RMSE (Baseline × Metamorphic Prediction):** 0.8744
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.214
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.169





Scenario 3D — Constant Speed Cruise

Metamorphic Relation Type: Composite (C), composed of Multiplicative (M), Additive (A), and Boundary (B) relations

Steady-state dynamic equilibrium

Description

This scenario evaluates the system's behavior under a steady-state operating condition characterized by constant speed and zero acceleration, representing stabilized cruising typically observed during highway driving.

In this scenario, the metamorphic transformation is applied from the beginning of the trajectory (sample index 0) and remains active throughout the entire sequence. Consequently, all samples are modified to enforce a constant speed condition and a boundary acceleration value equal to zero.

From a metamorphic testing perspective, this composite relation combines a **Multiplicative component**, associated with the scaling of speed toward a fixed constant value, an **Additive component**, associated with the adjustment of acceleration toward its equilibrium state, and a **Boundary component**, associated with enforcing the physical equilibrium condition where acceleration remains at zero.

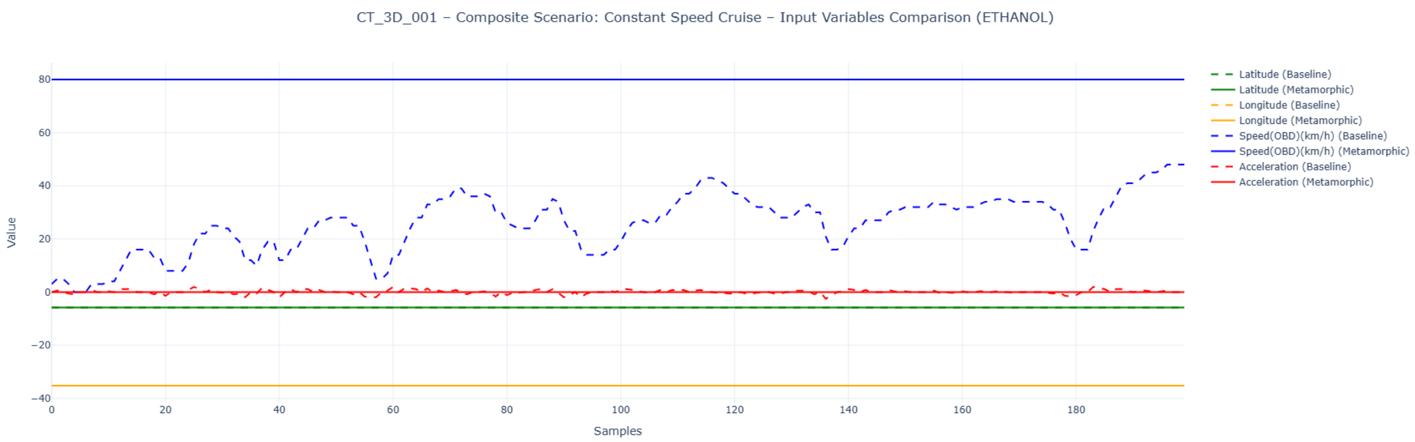
The test case models a dynamic equilibrium regime in which no transient events or external disturbances are present. Under such conditions, the system output is expected to exhibit stable and consistent behavior, reflecting the absence of acceleration-driven dynamics.

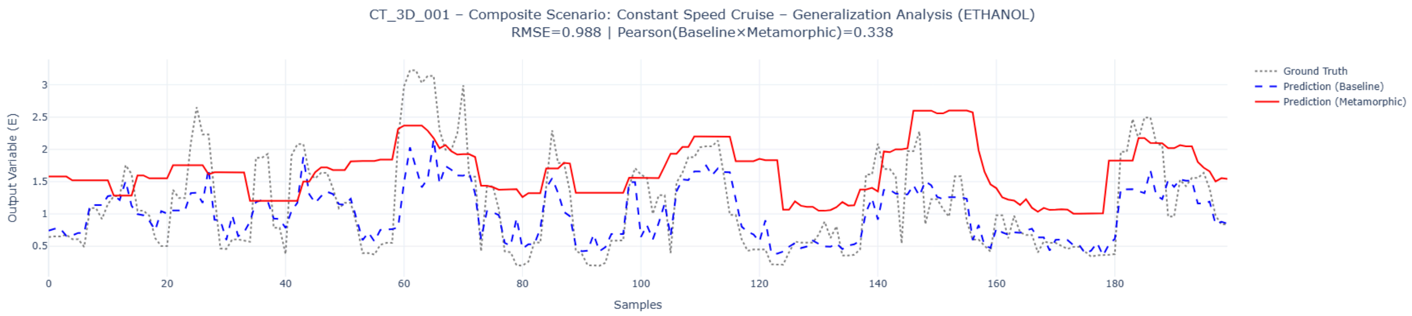
The objective is to assess whether the system maintains output stability, execution continuity, and coherent predictions when subjected to equilibrium input conditions.

Test Cases

CT_3D_001 — Composite Scenario (Constant Speed Cruise) — Ethanol

- **RMSE (Baseline × Metamorphic Prediction):** 0.9879
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.338
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.305





CT_3D_001 — Composite Scenario (Constant Speed Cruise) — Gasoline

- **RMSE (Baseline × Metamorphic Prediction):** 1.0376
- **Pearson Correlation (Baseline × Metamorphic Prediction):** 0.544
- **Pearson Correlation (Ground Truth × Metamorphic Prediction):** 0.409