Robust Timestamp Correction for Multi-Camera Trajectory Reconstruction in Road Safety Analysis

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Why This Matters: Road Safety & Vision Zero

Vision Zero

Prevent fatalities through near-miss detection.

Multi-Camera Systems

Fuse views for better trajectory reconstruction.

Surrogate Safety Measures

Measure conflict risk before crashes happen.

TTC (Time-to-Collision): time remaining until two users collide at current speeds
PET (Post-Encroachment Time): time gap after one user leaves a conflict zone before the next enters

Problem Statement: Timestamp Anomalies in Multi-Camera Data

Expected

$t_1 < t_2 < t_3 < \ldots$ Strictly increasing, uniquely indexed

Observed in MIA STRIKE data

- Timestamp freezes
- Duplicated metadata
- Variable metadata
- Origin unclear

Downstream Impact

Fragmented trajectories

Stalled timestamps break cross-camera track links

Corrupted TTC & PET

$\Delta t = 0$ causes division by zero or ambiguous ordering

Silent failure

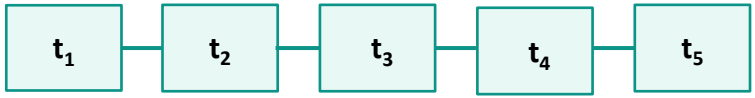
No error is raised - analysis continues

Case Study: MIA STRIKE Real-World Dataset

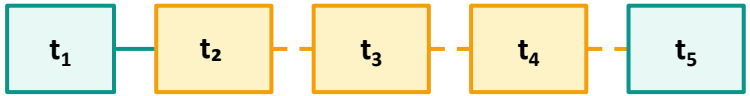
Dataset at a Glance

Project:	MIA STRIKE (Mobiliteit Innovatief Aanpakken)
Location:	Urban roadside intersection, Belgium
Setup:	Two-camera roadside system
Goal:	Proactive traffic conflict & near-miss detection
Anomaly:	Recurring timestamp freezes (100–400 ms)

Expected: Strictly increasing timestamps



Observed: Frozen / Duplicated timestamps



Frames 2–4: visually different content but timestamp frozen

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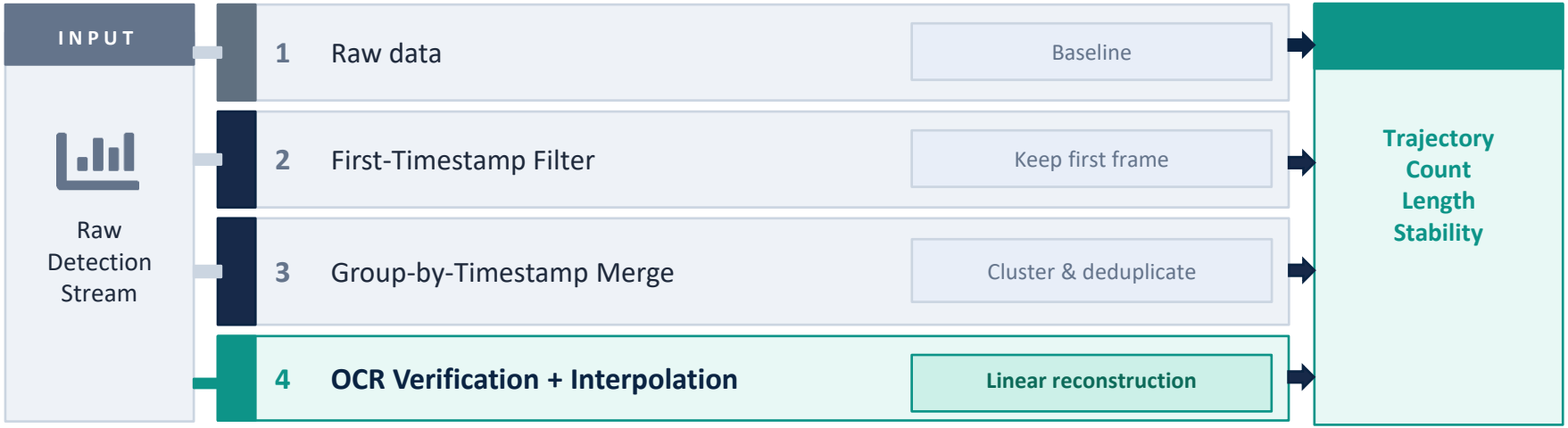
Same timestamp - visually different frames

Frame A | t = 14:47:42.273128

Frame B | t = 14:47:42.273128 (car has moved!)

Methodology: Timestamp Correction Pipeline



← All four processed streams evaluated in parallel →

Trajectory Count

No. of unique trajectory IDs reconstructed

Avg Trajectory Length

Mean frames per tracked object

Motion Stability

Speed coefficient of variation (CV)

Four Correction Strategies

RAW

Raw Baseline

No correction applied

Fragmented trajectories & speed spikes

FT

First-Timestamp Filter

Keep first frame per duplicate timestamp

Discards valid new detections

GT

Group-by-Timestamp Merge

Cluster & deduplicate frames at same t

Timestamp error remains uncorrected

IP

Timestamp Interpolation

Linearly reconstruct frozen t — restores valid timeline

Best result · restrict to gaps < 1 s

Each strategy applied to the same raw stream → results compared on trajectory count, length, and speed stability

OCR Verification

Root Cause Diagnosis

1. Extract embedded timecodes via OCR
2. Compare against system timestamps
3. Both frozen frames still differ
4. **Fault: camera clock, not detection**

Timestamp Interpolation

$$\hat{t} = t_a + [(j - a + 1)/(b - a + 2)] \cdot (t_{b+1} - t_a)$$

Result

Strictly Increasing

$\hat{t}_a < \hat{t}_{a+1} < \cdots < \hat{t}_b$

Range

Freeze intervals 100 – 400 ms

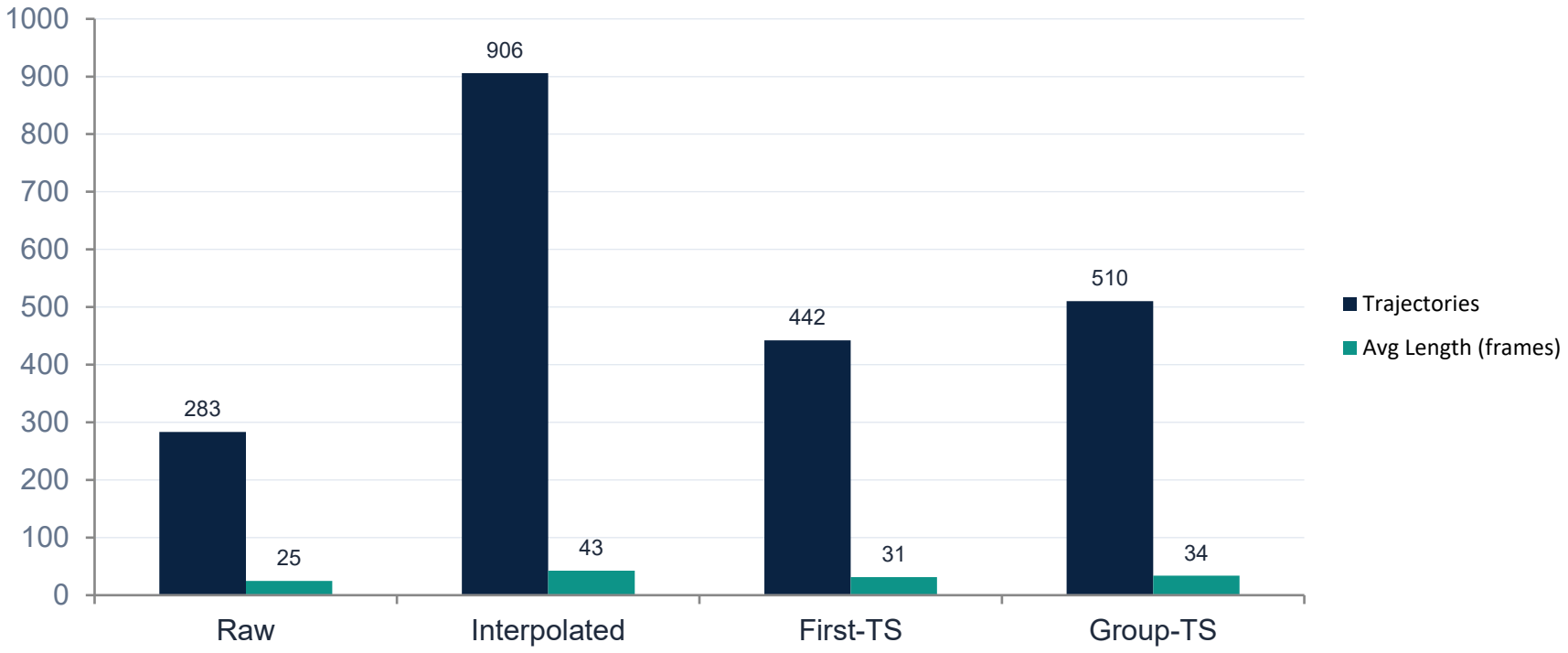
Threshold

Short gaps only (< 1 s)

All detection metadata preserved - only timestamps corrected

Results: Trajectory Count & Average Length

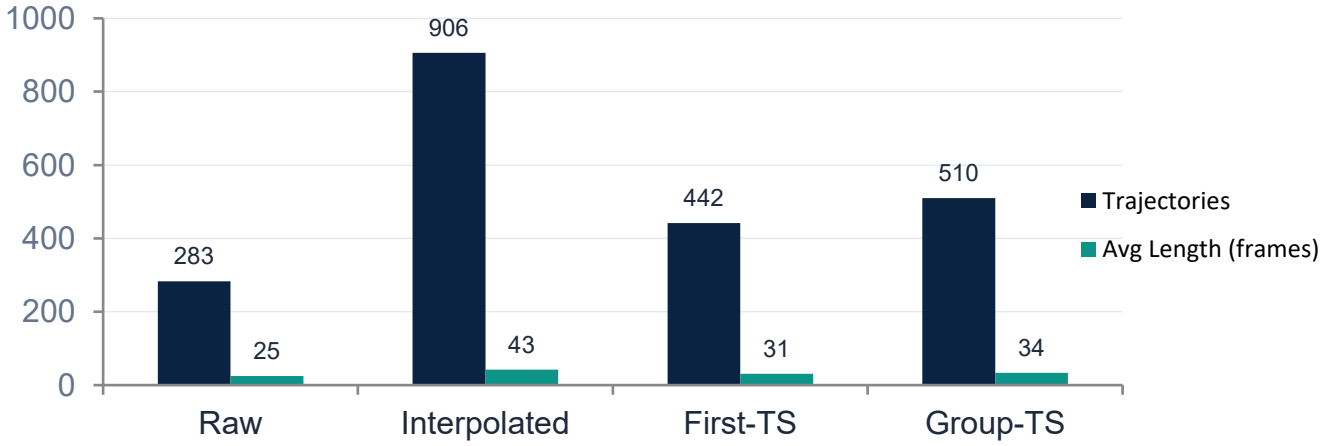
▲ +220% more trajectories | +73% longer average length vs. Raw



Results: Trajectory Count & Average Length

906	42.5	283	24.6
trajectories (Interpolated)	avg frames/object (Interpolated)	trajectories (Raw)	avg frames/object (Raw)

▲ +220% more trajectories | +73% longer average length vs. Raw



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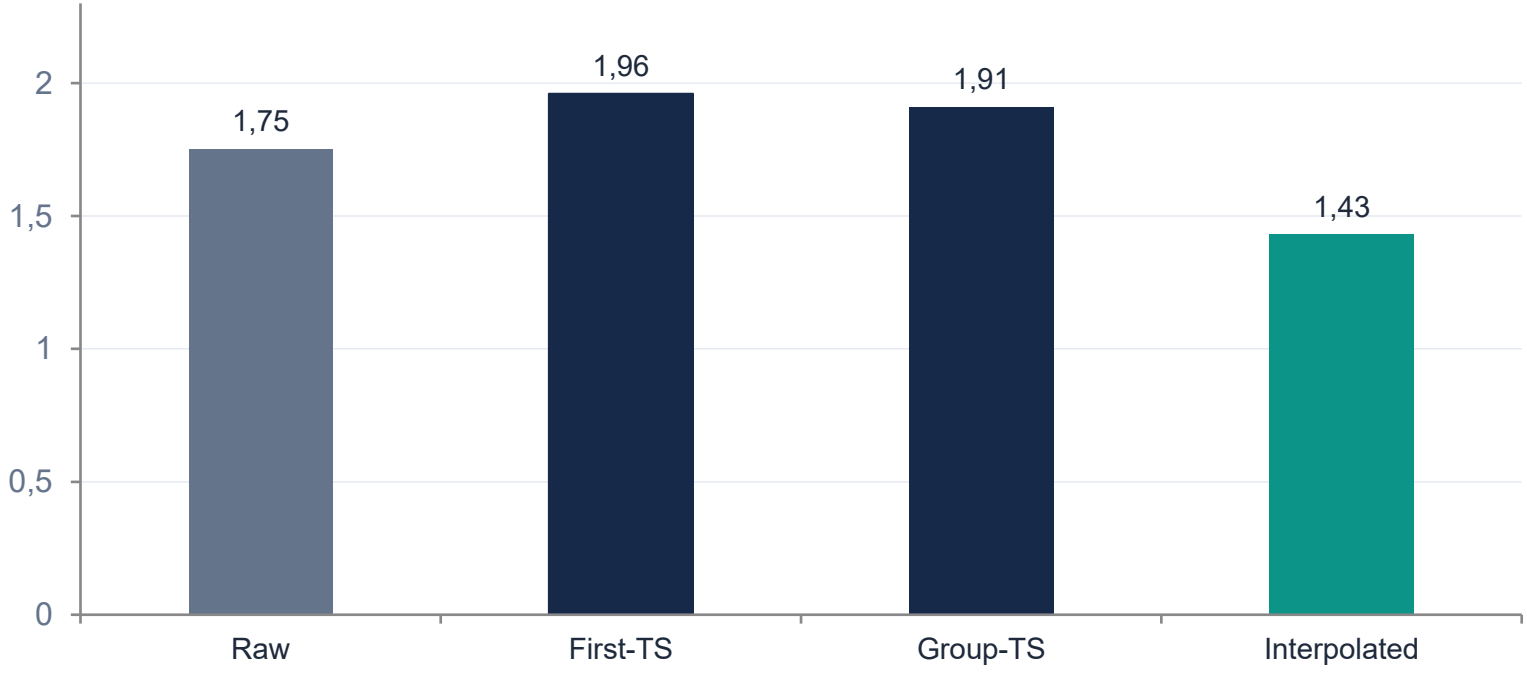
Interpolated vs Raw trajectories - real MIA-STRIKE footage

Results: Motion Stability & Speed Consistency

Lower CV = smoother, more reliable speed estimates



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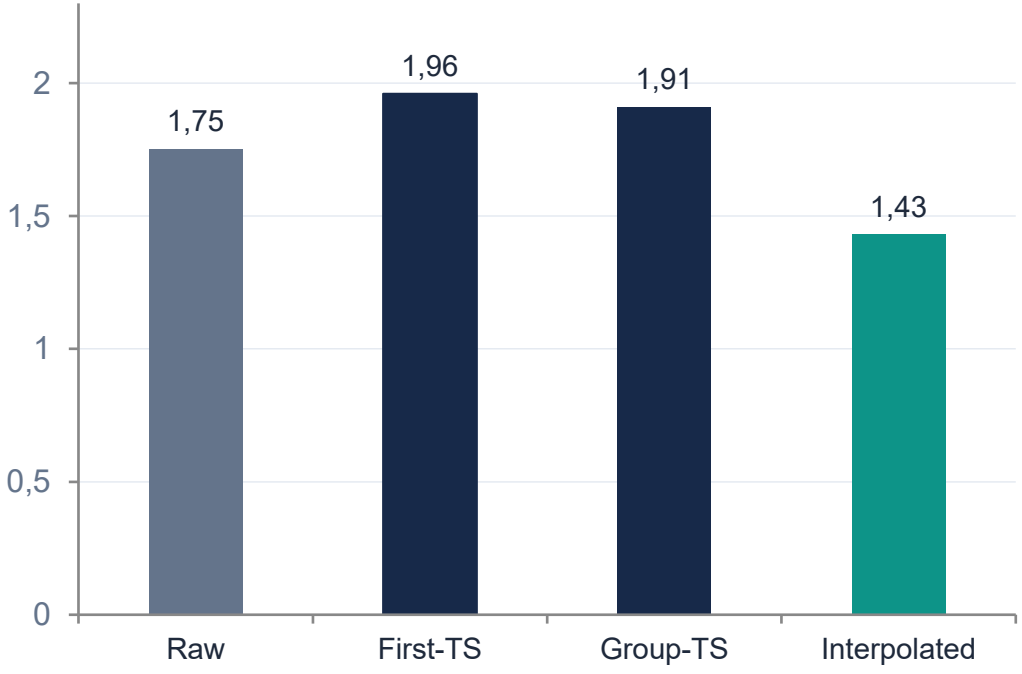

1.43 — **Interpolated - lowest CV**

Smoother speed, fewer discontinuities

1.75 — **Raw - baseline**

Speed resets from stalled timestamps

1.96 — **First-TS - worst**

Information loss amplifies noise

Safety Impact: How Timestamp Faults Corrupt TTC & PET

Timestamp faults propagate silently into both safety measures - invalidating results without raising any error.

TTC — Time-to-Collision

Requires

Instantaneous velocity from consecutive Δt

Fault

Frozen Δt = 0 → division by zero → meaningless TTC

Fixed by

Interpolation restores non-zero Δt between every frame pair

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PET — Post-Encroachment Time

Requires

Accurate temporal ordering across camera streams

Fault

Duplicate timestamps → ambiguous ordering → incorrect PET

Fixed by

Interpolation enforces strict ordering, resolving cross-camera ambiguity

Practical Implications & Future Work

Recommendations for Agencies

1. Validate timestamps before any analysis
2. Use OCR to detect embedded clock freezes
3. Interpolate only for gaps < 1 s
4. Flag corrected intervals in output metadata

Future Work

Formal interpolation constraints

Establish formal constraints on interpolation - define acceptable temporal-gap thresholds relative to frame rate and motion dynamics.

Conclusion

Temporal recalibration is essential for trustworthy trajectory-based road safety analysis.

01

Root Cause Found

OCR verification confirmed timestamp faults originate in the camera clock, not the detection pipeline.

02

Best Method: Interpolation

906 vs 283 trajectories (+220%). 42.5 vs 24.6 avg length. Speed CV 1.43 vs 1.75.

03

Practical Guidance

Validate timestamps before any safety analysis. Interpolate only for short gaps (< 1 s).

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