



TECHNICAL WHITE PAPER

# From detection to measurement

A technical framework for  
3D near-miss risk grading



Defensible evidence for road safety decisions.

DOCUMENT GUIDE

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DOCUMENT INFORMATION

| Prepared by                         | Source issue                                  | Presentation edition                 |
|-------------------------------------|-----------------------------------------------|--------------------------------------|
| Simon Maselli<br>XVision AI Systems | Rev 1 • July 2026<br>Tender submission source | Customer layout<br>24 September 2026 |

This edition retains the source framework, equations, target tolerances and references. Illustrative results and proposed risk bands are labelled separately from validated field performance.

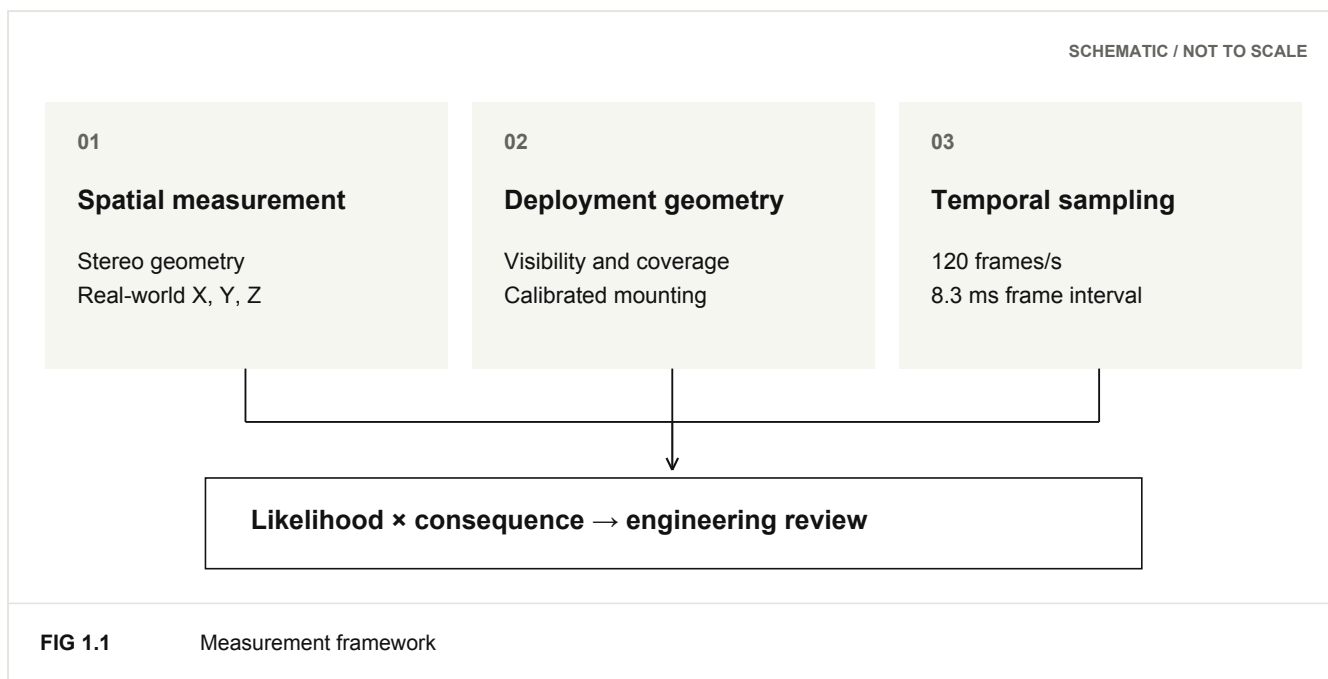
## 01 / EXECUTIVE SUMMARY

# Evidence before intervention

Near-miss analysis is useful when it gives transport engineers reliable evidence about how road users interact, how close they come to conflict and what the consequences could be.

Crash records remain important, but they describe events that have already happened. Trajectory-based surrogate safety measures can help authorities investigate conflict exposure before a collision occurs. That requires more than identifying objects in video: it requires a measurement process with known uncertainty.

This paper brings together three design choices: three-dimensional stereo measurement, deployment geometry that maintains visibility, and temporal sampling at 120 frames per second. Together, they support the reconstruction of road-user paths and the estimation of Time-to-Collision (TTC), Post-Encroachment Time (PET) and minimum separation.



Three complementary controls on measurement quality. Each must be checked under the conditions of the deployment.

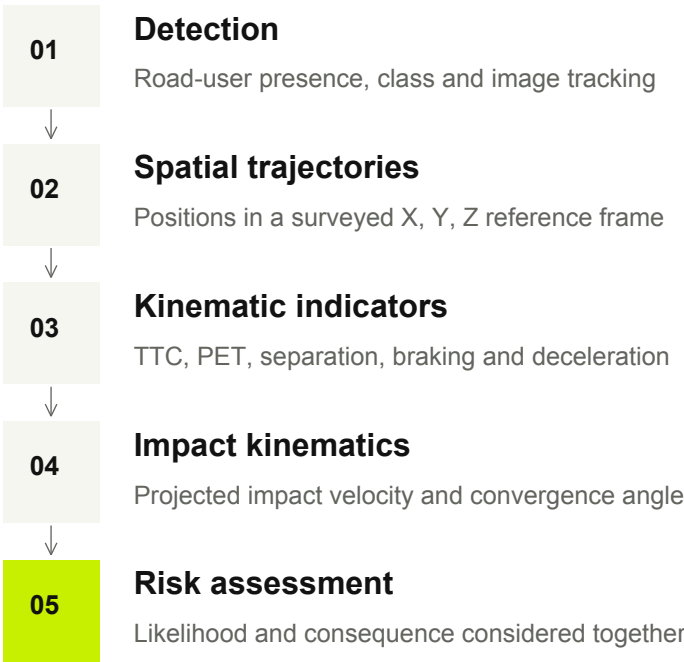
## Engineering principle

Measure the trajectory, quantify uncertainty and keep the supporting evidence with the assessment. Engineers remain responsible for intervention decisions.

02 / DETECTION-TO-MEASUREMENT FRAMEWORK

# From objects to trajectories

Object detection establishes that a road user is present. Quantitative conflict assessment also needs physical position, motion and interaction geometry. Image-space bounding box centroids alone do not provide those measurements.



MEASUREMENTS TO RETAIN

| Geometry and motion                     | Conflict and consequence                     |
|-----------------------------------------|----------------------------------------------|
| 3D coordinate trajectories              | Time-to-Collision and Post-Encroachment Time |
| Instantaneous speed vectors             | Braking onset latency and deceleration       |
| Path convergence angles                 | Predicted impact velocity                    |
| Minimum boundary-to-boundary separation | Predicted impact angle                       |

Surrogate safety measures support proactive assessment (Hayward, 1972; FHWA, 2008). Their interpretation depends on trajectory quality, clear event definitions and the conditions under which a potential collision is projected.

## 03 / STEREO VISION AND DEPTH RECONSTRUCTION

# Measuring space

A monocular image projects a three-dimensional scene onto a two-dimensional sensor. Planar homography maps image points onto an assumed road plane. Its accuracy depends on calibration, the reference surface and the point on each road user that is tracked.

Road grade, crossfall, vertical curvature, vehicle pitch and changes in camera pose can violate a planar model. A change in object height can then appear as a change in ground position. These effects need to be included in the measurement uncertainty.

A calibrated stereo pair estimates depth by triangulating corresponding image features from two synchronised cameras. The known baseline and focal length relate image disparity to depth (Hartley and Zisserman, 2004).

$$Z = f B / d \quad (3-1)$$

$$\delta Z \approx Z^2 \delta d / (f B) \quad (3-2)$$

**Z** depth (m) · **f** focal length (pixels) · **B** baseline (m)

**d** disparity (pixels) · **δd** disparity error (pixels) · **δZ** depth uncertainty (m)

## Uncertainty remains part of the measurement

Depth uncertainty increases approximately with the square of range and decreases with larger baseline and focal length. The source uses 0.1-0.2 pixels as an illustrative sub-pixel disparity error; achieved performance must be established for the actual hardware and scene.

Stereo geometry makes the depth calculation explicit. It does not remove the need to validate calibration, image quality, occlusion and uncertainty across the measurement zone.

# Projection and triangulation

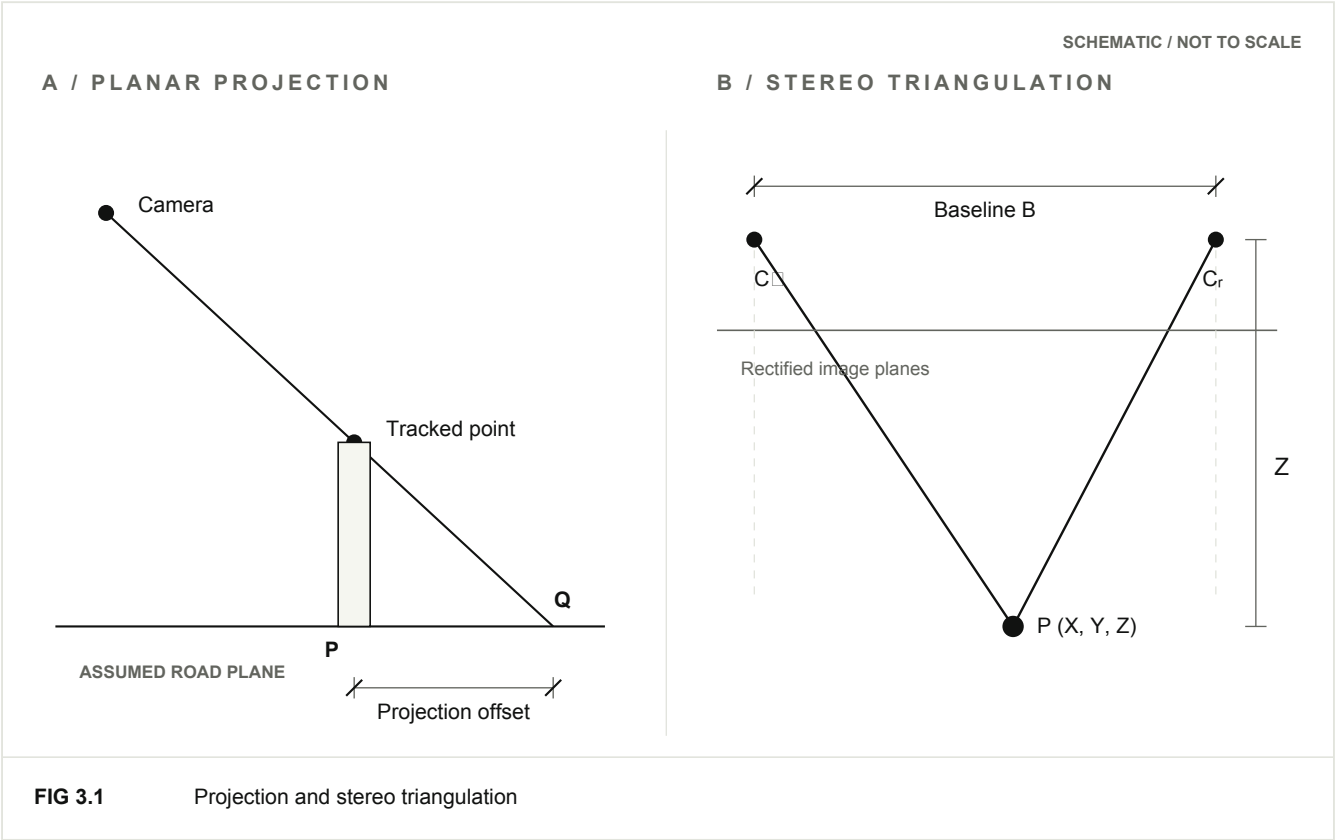


FIG 3.1 Projection and stereo triangulation

A: an elevated tracking point projects to a different point on the assumed road plane. B: two calibrated views constrain the same spatial point through intersecting sight lines.

| Measurement         | Single-camera homography                  | Calibrated stereo                           |
|---------------------|-------------------------------------------|---------------------------------------------|
| Depth / coordinates | Mapped onto a reference plane             | Triangulated 3D coordinates                 |
| Trajectory / speed  | Derived on the projected plane            | Derived from 3D displacement                |
| Impact angle        | Sensitive to projection geometry          | Derived from 3D motion vectors              |
| Confidence          | Depends on model validity and calibration | Depends on calibration, disparity and range |

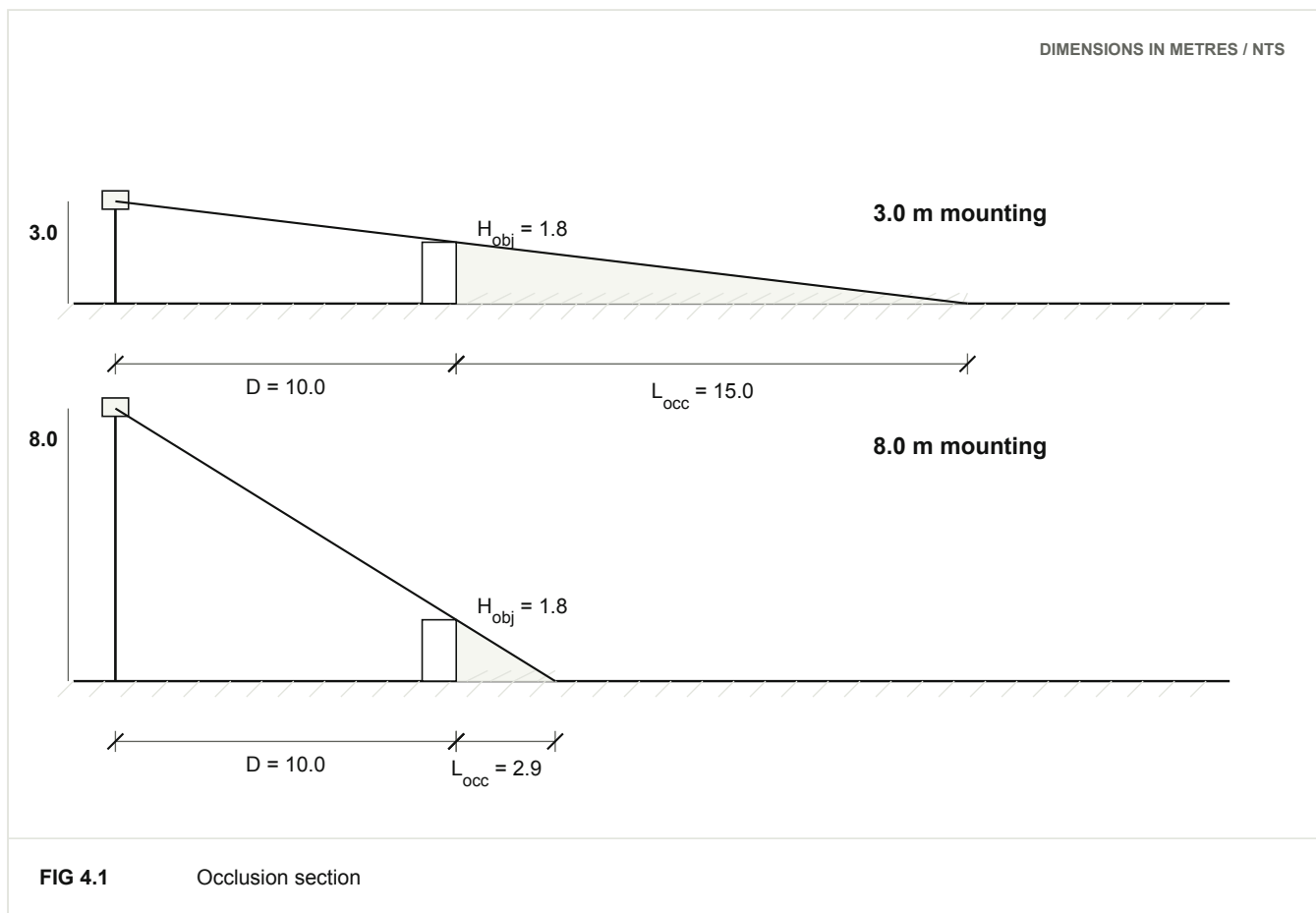
## 04 / DEPLOYMENT GEOMETRY

# Height changes what you can see

Low mounting positions create shallow sight lines. Larger vehicles can conceal pedestrians, cyclists and smaller vehicles behind them. Mounting height therefore affects trajectory continuity as well as the area visible to the sensor.

$$L_{occ} = D H_{obj} / (H_{cam} - H_{obj}) \quad (4-1)$$

Level road; rigid camera; stationary blocker;  $H_{cam} > H_{obj}$ .  $D$  is measured to the idealised blocking face. This simplified model does not represent vehicle length or a full 3D visibility analysis.



Increasing height reduces the idealised occluded ground length. Both sections use the same horizontal and vertical drawing scale for comparison.

04 / COVERAGE AND ENGINEERING TRADE-OFFS

# Select height for the site

For a 1.8 m blocker at 10 m horizontal range, the simplified model gives the following occlusion lengths. Values are calculated from Equation (4-1); percentage reductions use unrounded results.

| Camera height | Occluded length | Reduction vs 3 m |
|---------------|-----------------|------------------|
| 3.0 m         | 15.0 m          | Baseline         |
| 4.0 m         | 8.2 m           | 45.5%            |
| 5.0 m         | 5.6 m           | 62.5%            |
| 6.0 m         | 4.3 m           | 71.4%            |
| 8.0 m         | 2.9 m           | 80.6%            |

## Visibility must be balanced with resolution

| Height | Design considerations                                                                                                                     |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------|
| 3.0 m  | High pixel density near the pole, but substantial occlusion and limited conflict-zone coverage. Assess carefully for multi-lane analysis. |
| 5.0 m  | A practical height to evaluate for existing poles and temporary masts, subject to local infrastructure and coverage.                      |
| 6.0 m  | A candidate balance between resolution, occlusion and trajectory continuity. Confirm suitability for the intersection.                    |
| 8.0 m  | Improved visibility; check focal length, stereo baseline, far-range accuracy, pole stiffness and wind-induced motion.                     |

There is no universal optimum height. Confirm the target zone, pixel density, slant range, structural stability and safe installation requirements before selecting the final mounting arrangement.

05 / TEMPORAL MEASUREMENT

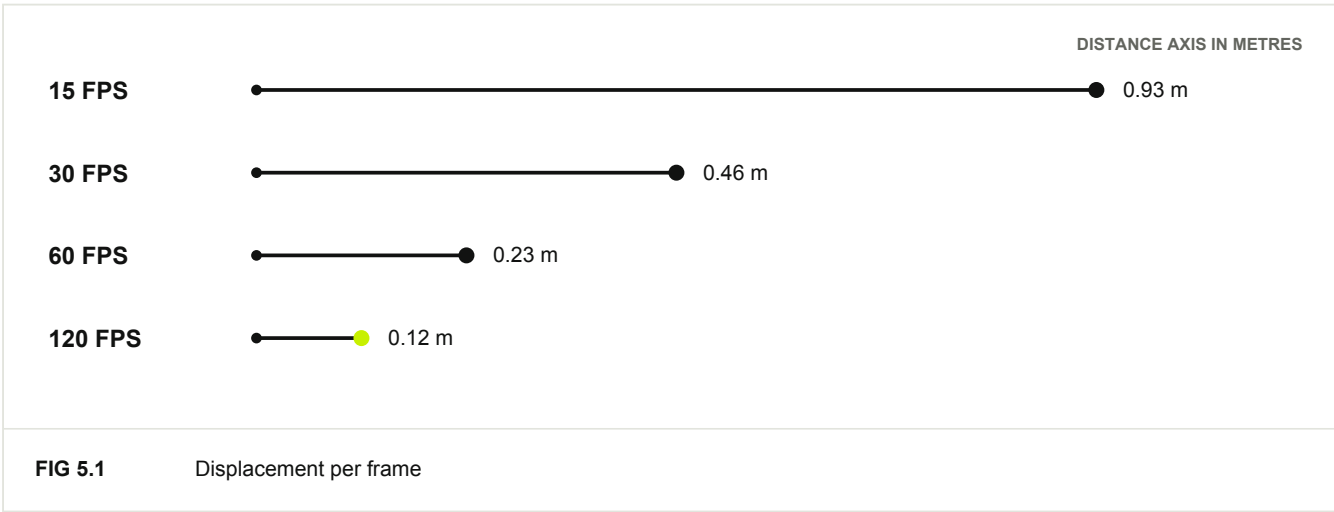
# Measure between frames

Frame rate determines the interval between observations. At 50 km/h (13.89 m/s), a vehicle travels about 0.46 m between frames at 30 FPS and about 0.12 m at 120 FPS. Higher sampling density supports closer examination of rapid braking and conflict events.

$$\Delta x = v \Delta t = v / FPS$$

(5-1)

| Frame rate | Frame interval | Travel per frame at 50 km/h |
|------------|----------------|-----------------------------|
| 15 FPS     | 66.7 ms        | 0.93 m                      |
| 30 FPS     | 33.3 ms        | 0.46 m                      |
| 60 FPS     | 16.7 ms        | 0.23 m                      |
| 120 FPS    | 8.3 ms         | 0.12 m                      |

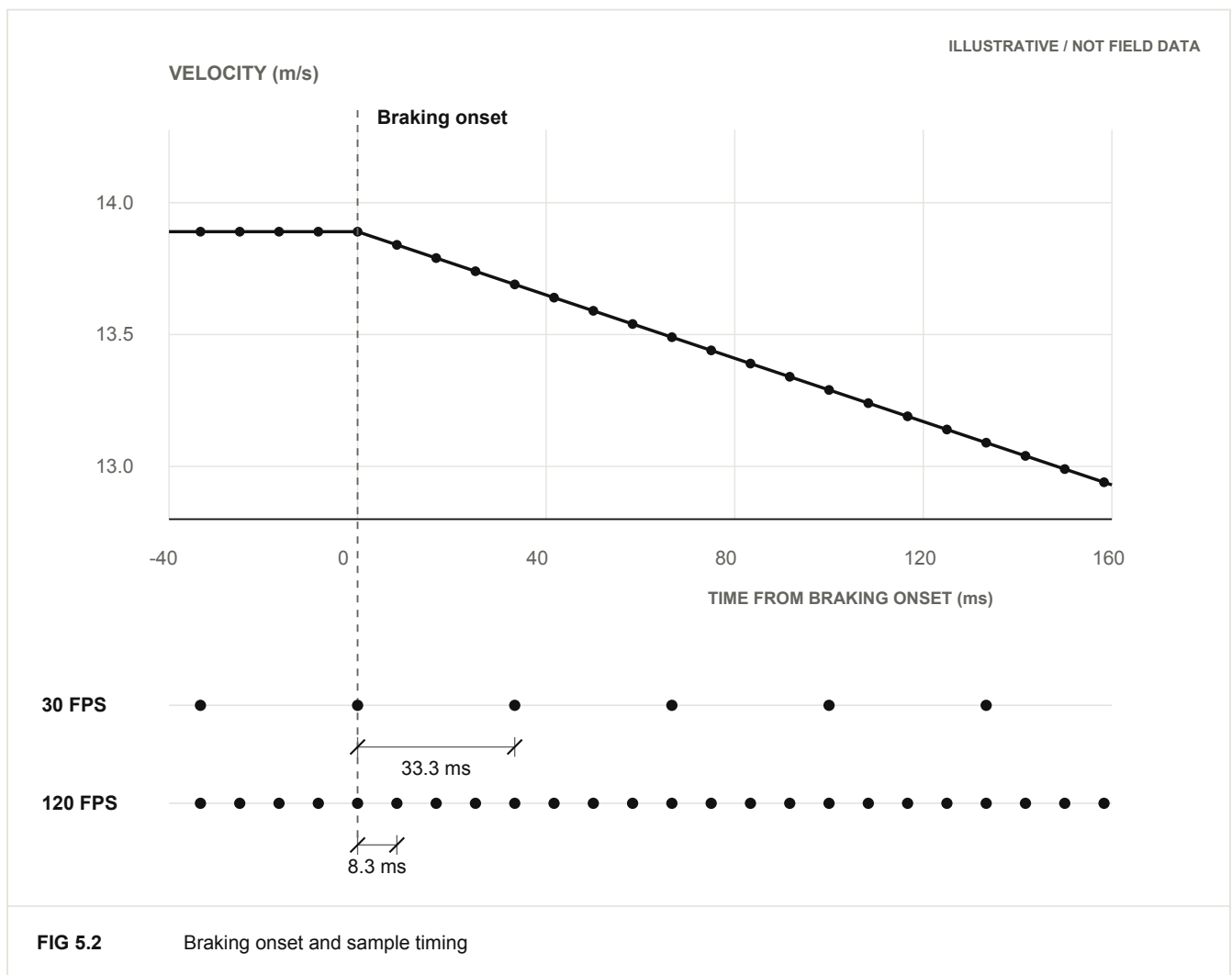


Frame interval is a sampling limit, not the complete detection latency. Exposure, synchronisation, processing and tracking also affect the time and accuracy of an event estimate.

## 05 / ENGINEERING REFERENCE

# Sampling a braking event

A braking onset can occur between frames. The next observation is available within one frame interval, depending on its phase relative to the event. The comparison below illustrates sampling density; it is not a measured algorithm response.



## What the additional samples provide

More observations can reduce interpolation gaps around braking onset and closest approach. They do not guarantee a particular TTC error or deceleration accuracy: those depend on spatial noise, filtering, event definitions and validation.

## 06 / RISK ASSESSMENT

# Likelihood and consequence

The same TTC can describe very different interactions. A 1.2 s TTC in a low-speed merge and a 1.2 s TTC between a heavy vehicle and a pedestrian do not imply the same potential harm.

$$\text{Risk} = \text{Likelihood} \times \text{Consequence}$$

(6-1)

## Likelihood indicators

**Time-to-Collision:**  $\text{TTC}(t) = g(t) / v_{\text{close}}(t)$ , where  $g$  is the remaining gap and  $v_{\text{close}}$  is the positive closing speed along a defined collision path. This scalar relation applies only where the assumed motion leads to collision.

**Post-Encroachment Time:**  $\text{PET} = t_{\text{entry,B}} - t_{\text{exit,A}}$ . It measures the interval between road user A leaving a shared conflict area and road user B entering that area.

**Minimum separation:** the smallest distance between the physical boundaries of the interacting road users. This differs from the distance between tracking-box centres.

## Consequence indicators

Projected impact speed, impact angle and road-user vulnerability provide context for potential harm. Impact speed influences kinetic energy; collision configuration influences how that energy is transferred and the protection available to the road user.

TTC and PET are surrogate indicators, not calibrated collision probabilities. Treat the proposed risk matrix as a prioritisation aid requiring local calibration and engineering judgement.

## 06 / PROPOSED RISK MATRIX

# A structured basis for review

The source framework combines three likelihood bands with three consequence categories. The actions below are indicative responses for engineering review; they are not automatic design instructions.

| PROPOSED BANDS / SITE VALIDATION REQUIRED       |                                               |                                                   |                                            |
|-------------------------------------------------|-----------------------------------------------|---------------------------------------------------|--------------------------------------------|
|                                                 | <b>LOW</b><br>Vehicle-to-vehicle<br>Low speed | <b>MEDIUM</b><br>Vehicle-to-vehicle<br>High speed | <b>HIGH</b><br>Vehicle-to-VRU<br>Any speed |
| <b>HIGH</b><br>TTC < 1.0 s<br>PET < 1.0 s       | <b>Treat</b>                                  | <b>Priority treat</b>                             | <b>Critical intervention</b>               |
| <b>MEDIUM</b><br>TTC 1.0-1.5 s<br>PET 1.0-2.0 s | <b>Review</b>                                 | <b>Treat</b>                                      | <b>Priority treat</b>                      |
| <b>LOW</b><br>TTC > 1.5 s<br>PET > 2.0 s        | <b>Monitor</b>                                | <b>Monitor</b>                                    | <b>Review</b>                              |

**FIG 6.1** Likelihood × consequence

**VRU:** vulnerable road user. Thresholds are reproduced from the proposed source framework. Where TTC and PET fall into different bands, the aggregation rule must be defined before operational use.

**Indicative actions:** Monitor = continued observation; Review = passive safety audit; Treat = consider signal adjustment; Priority treat = active intersection treatment; Critical intervention = assess geometric redesign. Select an intervention only after reviewing the evidence and site context.

# Validate before operational use

A structured deployment process establishes whether the measurements are suitable for the intended safety assessment. Installation alone does not demonstrate accuracy.

01

## Assess the site and geometry

Survey the conflict zone. Select sensor position, mounting height and viewing orientation to balance visibility, occlusion, coverage and stereo measurement range.

02

## Test alternative heights

Use an adjustable temporary mast where appropriate. Compare occlusion, field of view and trajectory continuity under representative traffic conditions before committing to permanent works.

03

## Run passive shadow mode

Observe without operational alerts, typically for 7-14 days in the proposed workflow. Check trajectory stability, spatial consistency and calibration. Retain the evidence for acceptance review.

04

## Report the engineering findings

After validation, combine trajectories, surrogate measures and conflict evidence in a formal report. Explain the case for any operational, signal-timing or geometric intervention.

08 / MEASUREMENT VALIDATION AND QUALITY ASSURANCE

# Make accuracy verifiable

Use independently surveyed reference points and controlled vehicle runs to quantify error. Validate at installation, after changes to camera pose or calibration, and periodically during operation.

PROPOSED TARGETS FROM THE SOURCE PAPER

| Metric           | Target                        | Why it matters                                    |
|------------------|-------------------------------|---------------------------------------------------|
| Spatial position | ±0.10 m within 25 m           | Boundary separation and false conflict triggers   |
| Speed            | ±1.0 km/h in controlled runs  | Projected impact velocity and energy estimates    |
| Heading vector   | ±2.0°                         | Convergence angle and collision configuration     |
| Braking onset    | 8.3 ms at 120 FPS*            | Timing of deceleration and pre-braking TTC        |
| TTC / PET        | ±0.05 s                       | Stability of conflict likelihood grading          |
| Classification   | ≥99.0% continuous label match | Consistent road-user vulnerability classification |

\*8.3 ms is approximately one 120 FPS frame interval. It is not, by itself, a demonstrated end-to-end braking detection latency. State the measurement method and timing reference when validating this target.

## Report performance with its conditions

The targets above are proposed acceptance criteria, not evidence of achieved performance. Record the test zone, range, lighting, traffic conditions, sample sizes and error definition alongside the results. Confirm the required tolerances with the responsible engineer.

## 09 / ENGINEERING IMPLICATIONS

# A defensible measurement chain

Useful near-miss evidence connects the road-user trajectory to the decision it supports. The strength of that evidence depends on spatial accuracy, visibility, temporal resolution and independent validation.

Stereo geometry provides a physical basis for reconstructing three-dimensional positions. Mounting geometry determines which interactions remain visible. Higher-frequency sampling gives more observations through rapidly changing events. Each element contributes to a measurement chain that must be assessed as a whole.

## Apply the framework in context

Use TTC, PET, minimum separation and projected impact characteristics together. Keep assumptions and uncertainty close to the metrics, and distinguish proposed acceptance targets from field results. Consequence-aware grading can then help engineers compare conflicts and prioritise further investigation.

## Keep evidence with the location

Retain the supporting video, trajectories, measurement conditions and validation status with the assessment. This gives reviewers a clear route from an observed interaction to a finding, an intervention and a later assessment of what changed.

### FROM EVIDENCE TO ACTION

**Question → Evidence → Finding**  
**Decision → Intervention → Outcome**

## 10.1 / MATHEMATICAL REFERENCE

# Equations and notation

## STEREO DEPTH

$$Z = f B / d$$

Rectified, calibrated stereo geometry.

## DEPTH UNCERTAINTY

$$\delta Z \approx Z^2 \delta d / (f B)$$

First-order disparity-error propagation; excludes other error sources.

## GROUND OCCLUSION

$$L_{occ} = D H_{obj} / (H_{cam} - H_{obj})$$

Level ground and  $H_{cam} > H_{obj}$ .

## PER-FRAME DISPLACEMENT

$$\Delta x = v \Delta t = v / FPS$$

Constant speed over the frame interval.

## TIME-TO-COLLISION

$$TTC(t) = g(t) / v_{close}(t)$$

Positive closing speed on a defined collision path.

## POST-ENCROACHMENT TIME

$$PET = t_{entry,B} - t_{exit,A}$$

A exits and B enters the same conflict area.

Notation distinguishes stereo disparity  $d$  (pixels) from conflict gap  $g$  (m). In the source,  $d$  was used for both. The PET notation here explicitly identifies exit and entry events.

10.2 / ILLUSTRATIVE COMPARISON

# Worked scenario and limitations

The source considers a 1,500 kg car travelling at 50 km/h (13.89 m/s) along the y-axis and a 75 kg pedestrian crossing at 1.5 m/s along the x-axis. Their paths intersect at the origin. At  $t = -1.20$  s, the driver brakes at  $-6.0$  m/s<sup>2</sup> and the pedestrian is at  $x = -1.80$  m.

The comparison below retains the source values to illustrate the proposed measurement differences. No test dataset or complete derivation is supplied for these outcomes; they must not be read as a field benchmark.

| Parameter          | Reference scenario     | 2D / 30 FPS            | Stereo / 120 FPS       |
|--------------------|------------------------|------------------------|------------------------|
| Onset delay        | 0 ms                   | 33.3 ms                | 8.3 ms                 |
| Minimum separation | 0.45 m                 | 0.91 m                 | 0.47 m                 |
| Deceleration       | -6.00 m/s <sup>2</sup> | -4.50 m/s <sup>2</sup> | -5.92 m/s <sup>2</sup> |
| TTC at onset       | 1.20 s                 | 1.10 s                 | 1.19 s                 |

## What can be calculated directly

At 50 km/h,  $v / \text{FPS}$  gives 0.463 m per frame at 30 FPS and 0.116 m at 120 FPS. Frame intervals are 33.33 ms and 8.33 ms respectively. These values follow directly from the stated speed and sampling rates.

## What requires supporting evidence

The stated separation, deceleration and TTC outcomes also depend on road-user geometry, initial vehicle position, sampling phase, tracking and filtering. Frame rate alone does not establish the listed TTC errors. The 0.91 m versus 0.45 m separation difference is approximately 102%, but its cause cannot be verified from the supplied scenario.

## 10.3-10.4 / TECHNICAL RECORD

# Assumptions and references

The framework assumes valid calibration, rectified stereo imagery, adequate image quality, survey control that meets the required tolerance, and representative road-user dimensions where illustrative calculations need them. Actual performance varies with environment, geometry, traffic and maintenance. Field validation is required for each operational deployment.

| Symbol                            | Meaning                                    | Unit    |
|-----------------------------------|--------------------------------------------|---------|
| $Z / B$                           | Depth / stereo baseline                    | m       |
| $f / d / \delta d$                | Focal length / disparity / disparity error | pixels  |
| $H_{\text{cam}} / H_{\text{obj}}$ | Camera / blocking-object height            | m       |
| $D / L_{\text{occ}}$              | Blocker range / occluded ground length     | m       |
| $\Delta x / \Delta t$             | Displacement / frame interval              | m / s   |
| $g / v_{\text{close}}$            | Conflict gap / closing speed               | m / m/s |
| TTC / PET                         | Time-to-Collision / Post-Encroachment Time | s       |

## References retained from the source

Allen, B. L., Shin, B. T., & Cooper, P. J. (1978). Analysis of Road Safety with Service Delay and Conflict Techniques. *Transportation Research Record*, 667, 12-21.

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Kusano, K. D., & Gabler, H. C. (2012). Safety benefits of active braking systems in real-world rear-end crashes. *Accident Analysis & Prevention*, 49, 275-285.

Laureshyn, A., Svensson, Å., & Hydén, C. (2010). Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and operationalisation. *Accident Analysis & Prevention*, 42(6), 1907-1917.