

Article

A Vision Zero-Oriented Diagnostic Framework for Complex Junctions Using UAV-Based Trajectory Analysis

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Abstract

This study presents a replicable diagnostic framework for analysing latent safety vulnerability at complex junctions by integrating UAV-based observation, trajectory extraction, movement-level operational performance modelling, and regulatory benchmarking. Grounded in Vision Zero/Safe System principles, the approach is demonstrated at Junction 50 of the A-66 motorway in Mieres (Spain), a constrained urban interchange where motorway access/egress overlaps with local cross-town movements. Two one-hour UAV datasets were collected during peak periods and processed with GoodVision to extract trajectories, turning-movement counts, origin–destination patterns and recurrent irregular manoeuvres. These outputs were combined with SIDRA INTERSECTION indicators (e.g., LOS, delay and capacity utilisation) and assessed against the Spanish geometric design standard to identify design–operation misalignment, including a targeted 3D sight-distance check at the stop-controlled exit. The results show systematic behavioural adaptations at critical decision points, including informal side-by-side queuing at nominally single-lane exits and queue bypassing via adjacent auxiliary areas, co-occurring with capacity-strained movements (LOS E–F) and normative inconsistencies in lane type/length and channelisation. The framework translates high-resolution behavioural evidence into intervention-relevant outputs (critical movements, concentration zones and explicit design–behaviour mismatches) without relying on crash frequency as the primary signal, supporting proactive prioritisation in constrained legacy layouts.

Keywords: Vision Zero; safe system approach; unmanned aerial vehicles (UAVs); trajectory-based analysis; regulatory benchmarking (Norma 3.1-IC)



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1. Introduction

Road traffic injury remains a persistent global public health burden and a core challenge for sustainable urban mobility. The World Health Organization estimates that approximately 1.19 million people die each year due to road traffic collisions [1]. In response, the Vision Zero paradigm emerged as an ethical and operational framework that rejects fatalities and serious injuries as “acceptable” externalities of transport systems. Introduced

in Sweden in 1997, Vision Zero assigns shared responsibility for safety outcomes to system designers and operators—alongside vehicle manufacturers, regulators, and users—and explicitly recognises that humans will make errors. The Safe System logic, therefore, prioritises road environments that reduce the probability of critical errors and mitigate their consequences when errors occur [2].

Yet, a recurring implementation gap remains: at the local scale, where interventions must be prioritised and justified, the analytical toolbox used to identify “where to act next” still often relies on crash records and conventional safety audits—data sources that may not adequately reveal how risk is generated dynamically at specific sites.

This gap is particularly consequential in complex urban junctions and interchanges. Such locations concentrate heterogeneous movements (e.g., motorway access/egress and local cross-town flows) within constrained footprints, often under legacy geometries and limited storage. Here, severe crashes may be relatively rare events in time, while exposure to conflict-prone interactions can be recurrent and systematic. In these settings, crash frequency alone may provide a weak or delayed signal, and traditional audits may struggle to capture behavioural adaptation and operational strain as they unfold. A Vision Zero-consistent approach, therefore, benefits from proactive diagnosis: identifying latent risk mechanisms and design-behaviour mismatches before they manifest in severe outcomes.

Against this background, this study develops and demonstrates a replicable diagnostic framework, grounded in Vision Zero/Safe System principles, that combines: (i) UAV-based observation of traffic operations, (ii) trajectory extraction and spatial-behavioural analysis, (iii) intersection performance modelling using SIDRA INTERSECTION, and (iv) compliance assessment against current Spanish geometric design standards (Norma 3.1-IC, Ministerio de Transportes). The framework is designed to identify latent risk mechanisms and design-behaviour mismatches—including systematic irregular manoeuvres, ambiguous geometric cues and oversaturated movements that amplify exposure—rather than infer crash causation from crash counts (Figure 1).

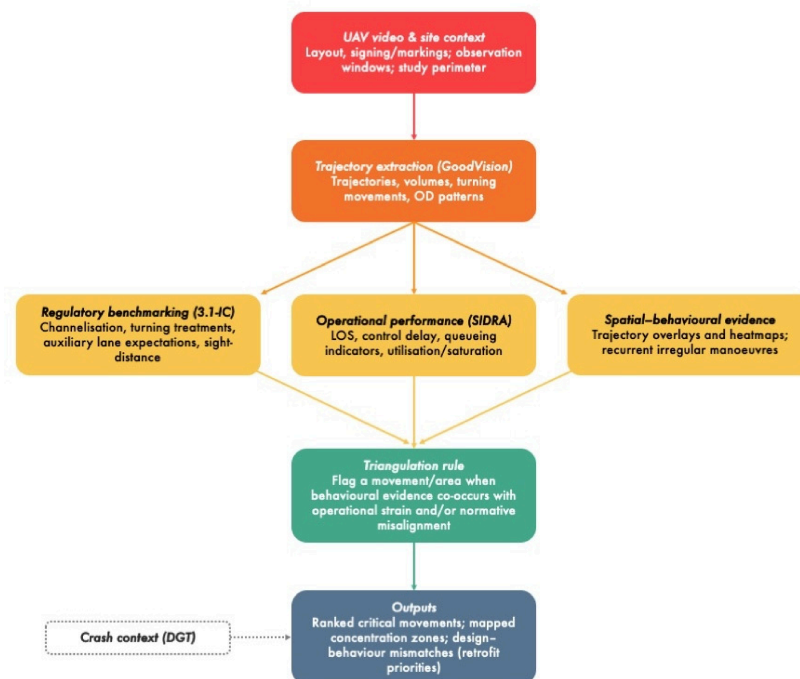


Figure 1. Vision Zero-oriented diagnostic logic and triangulation rule combining UAV-based observation, trajectory extraction, operational performance modelling (SIDRA) and regulatory benchmarking (Norma 3.1-IC). Official crash records are used only as contextual, descriptive evidence and are not part of the core triangulation rule.

The framework is applied to Junction 50 of the A-66 motorway in Mieres (Asturias, Spain), an urban interchange located in a topographically constrained valley setting. The junction concentrates motorway access/egress flows and local cross-town movements within a compact footprint, resulting in multiple conflict points and limited storage capacity. This makes it a suitable case for demonstrating the proposed proactive diagnostic workflow under constrained legacy geometry and peak-period operating conditions.

The remainder of the paper is structured as follows. Section 2 reviews the related literature and identifies the research gap addressed by this study. Section 3 describes the study area and the data collection campaign, including UAV flight specifications, trajectory extraction, operational modelling and regulatory benchmarking. Section 4 reports the results. Section 5 discusses implications for Vision Zero implementation in constrained legacy junctions and outlines limitations and transferability. Section 6 summarises the main conclusions.

2. Related Works and Research Gap

2.1. Vision Zero, Safe System and Proactive Safety Diagnosis

To date, Vision Zero implementation has been operationalised through measures intended to reduce kinetic energy and exposure, including speed management and lower urban speed limits [3], safer intersection configurations and conflict-point reduction [4], traffic calming and separation of vulnerable road users, and vehicle-based safety improvements such as Advanced Driver Assistance Systems (ADAS) for lane keeping, pedestrian detection, and automatic emergency braking [5]. Evidence from early-adopting jurisdictions indicates that systemic interventions can translate into measurable safety gains: Oslo reported zero pedestrian or cyclist fatalities in 2019 following speed reductions and urban space reallocation [6], and New York City's Vision Zero programme has been associated with reductions in injury rates since its launch in 2014 [7]. Yet, a recurring implementation gap remains: at the local scale, where interventions must be prioritised and justified, the analytical toolbox used to identify “where to act next” still often relies on crash records and conventional safety audits—data sources that may not adequately reveal how risk is generated dynamically at specific sites.

In Spain, long-term road safety indicators have improved substantially, including marked reductions in interurban fatalities [8,9]. Current national indicators report a mortality rate of 26 deaths per million inhabitants [10], supported by sustained policy attention, infrastructure investment and enforcement measures [11,12]. Nevertheless, safety challenges persist in urban contexts, where intersections and access points remain overrepresented in crash occurrence and where behavioural and contextual factors continue to shape injury severity [13]. Empirical studies have linked distraction, visibility conditions, pedestrian violations and non-use of safety devices to higher injury severity [14,15], and modelling work highlights the relevance of contextual constraints (e.g., lighting, lack of sidewalks) to fatal outcomes [16]. Alcohol-related crashes also exhibit higher injury severity when combined with demographic risk factors [17].

While this body of evidence is essential for national-level strategies, it does not in itself provide a method for diagnosing site-specific risk mechanisms at constrained junctions, where the central issue is often the interaction between geometric cues, demand patterns and user interpretation.

2.2. UAV-Based Traffic Observation and Trajectory-Based Safety Analysis

A growing methodological opportunity lies in unmanned aerial vehicles (UAVs) paired with computer vision. UAVs provide high-resolution overhead observation that can capture trajectories, interaction patterns and atypical manoeuvres with a level of detail

that is difficult to achieve with fixed cameras or conventional counting stations [18–21]. When processed through vision-based analytics, UAV video can be translated into turning-movement counts, origin–destination matrices, demand profiles, and spatial heatmaps, supporting quantitative modelling and behavioural interpretation [22,23]. Conceptually, this aligns with Vision Zero’s proactive logic: rather than waiting for crashes to accumulate, analysts can observe whether a layout systematically induces adaptation—such as lane misuse, late merges, queue bypassing or unanticipated lane changes—that increases exposure to unsafe interactions.

However, much of the UAV-based literature still treats trajectory reconstruction and behavioural observation as ends in themselves, with less emphasis on integration into a governance-relevant diagnostic workflow. In real-world decision contexts, infrastructure operators often require evidence that links observed behaviour to (i) operational performance and capacity strain and (ii) normative benchmarks, especially in legacy layouts where retrofit options are constrained and where design compliance may deviate from current standards. Without such integration, high-resolution observation risks remaining descriptive rather than actionable.

2.3. Research Gap and Contribution of This Study

Recent UAV-based studies have substantially advanced traffic monitoring, trajectory extraction and proactive safety analysis. Broad reviews show that UAVs combined with artificial intelligence have been applied to traffic operations, safety assessment and traffic simulation, while also identifying persistent challenges related to data integration, weather dependence, privacy and scalability [24]. Empirical applications have demonstrated the value of UAV video for extracting vehicle trajectories, identifying shockwaves, estimating traffic-flow parameters and analysing congestion patterns at intersections, ramps and interchange areas [25–28]. Other studies have gone further by using UAV-derived trajectories to support proactive safety monitoring and to compute surrogate safety measures such as Time-to-Collision, Post-Encroachment Time or extended TTC in intersections, roundabouts and diverging areas [29–33].

Nevertheless, three limitations remain relevant for the present study. First, many UAV-based applications focus primarily on data extraction, trajectory reconstruction, traffic-state identification or conflict quantification, with less attention to how the resulting evidence can be translated into implementable road-design decisions. Second, trajectory-based safety studies often treat behavioural indicators and operational performance separately, rather than combining observed manoeuvres with movement-level delay, saturation and queueing. Third, the link between observed behaviour and geometric design standards is rarely made explicit, even though retrofit decisions in legacy junctions require a clear connection between user behaviour, operational strain, sight-distance constraints and regulatory compliance. Recent work on infrastructure and environmental factors at intersections further supports the relevance of linking safety outcomes with geometric and operational road characteristics [34], while sight-distance studies confirm that visibility remains a design element with direct safety and operational implications [35].

The contribution of this study lies in addressing this integration gap. The proposed workflow does not rely on UAV video alone, nor does it aim to replace formal surrogate safety assessment. Instead, it combines UAV-derived behavioural evidence, SIDRA-based operational performance, 3D sight-distance assessment and benchmarking against Norma 3.1-IC in a single Vision Zero/Safe System-oriented diagnostic framework. This integration allows recurrent design–behaviour mismatches to be translated into intervention-relevant evidence for retrofit prioritisation at constrained legacy junctions.

The reviewed literature shows that UAV-based traffic observation can provide detailed behavioural and spatial evidence, while Vision Zero and the Safe System approach require proactive methods capable of identifying correctable infrastructure deficiencies before severe outcomes accumulate. However, a methodological gap remains between these two domains. Existing UAV-based studies often demonstrate the potential of aerial trajectories for traffic monitoring or behavioural observation, but fewer studies integrate this evidence with movement-level operational modelling, sight-distance assessment and regulatory benchmarking in a single workflow oriented towards infrastructure intervention.

This study addresses that gap by connecting four evidence layers: UAV-based trajectory observation, movement-level operational performance, geometric/sight-distance assessment and compliance-oriented benchmarking against current design standards. The framework does not aim to estimate crash probability directly. Rather, it identifies latent safety vulnerability through the convergence of recurrent non-standard manoeuvres, the concentration of trajectories in shared interaction areas, unstable operational conditions, sight-distance restrictions and design–operation inconsistencies.

The contribution of this paper is, therefore, methodological and applied. Methodologically, it provides a structured procedure for translating UAV-derived behavioural evidence into engineering-relevant outputs, including critical movements, concentration zones and explicit design–behaviour mismatches. From an applied perspective, it demonstrates how this procedure can be used in a constrained legacy interchange where conventional crash-based analysis may be insufficiently granular to support proactive intervention. This makes the proposed framework relevant for Vision Zero-oriented governance, particularly in urban or peri-urban junctions where redesign options are limited and where safety improvement requires targeted retrofit prioritisation.

3. Methods

3.1. Study Area and Urban Context

This study was conducted in Mieres (Asturias, Spain), a municipality located in the Caudal Valley with 36,195 inhabitants in 2023 (Figure 2). The urban form is constrained by steep valley slopes and a narrow floodplain, which has historically limited available land for transport infrastructure and promoted compact solutions. The city core develops along the Caudal River and is longitudinally crossed by two parallel corridors: the A-66 motorway and a conventional road running alongside it (La Autovía Oviedo-Campomanes sigue su camino, 1993).

Within this constrained morphology, Junction 50 of the A-66 functions not only as a motorway access/egress node but also as a local connector supporting significant cross-town movements (Figure 3). Although nominally a diamond interchange, the junction concentrates heterogeneous turning and merging movements within a reduced footprint, which limits storage lengths and increases the likelihood of queue spillback and trajectory interference. The interchange was originally built under the design logic of late-20th-century motorway programmes prioritising compactness. In Spain, diamond-type solutions of this kind were widely adopted for their reduced spatial requirements and construction simplicity [36]. Under current demand and user adaptation, several features (e.g., bifurcated exit geometry and permissive at-grade turning configurations) deviate from contemporary design recommendations and provide a relevant testbed for Vision Zero-oriented diagnostic assessment.

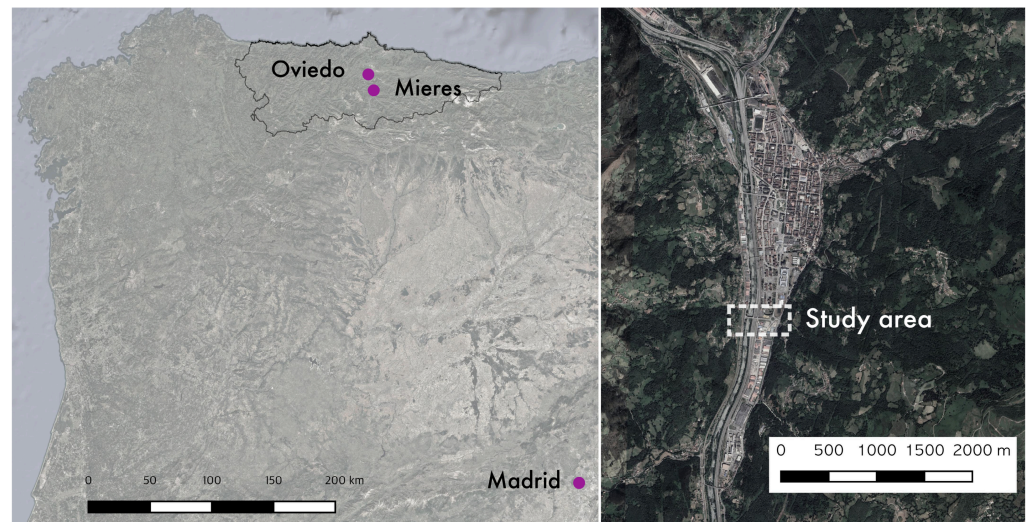


Figure 2. Location of Mieres and the study area. Source: authors' own elaboration.



Figure 3. Detailed view of the junction (Junction 50). Source: authors' own elaboration.

As part of the site-context assessment, a structured review of digital press archives and local media outlets was conducted to document publicly reported serious traffic incidents in the vicinity of Junction 50 over the last two decades (2000–2024) (see Appendix B for the press-archive triangulation records). The search identified eight cases that, while not consistently represented in official crash databases, described recurring configurations plausibly consistent with the site's geometric and operational constraints (e.g., rear-end collisions near uncontrolled exit areas, unsafe turning manoeuvres, and driver confusion associated with bifurcated layouts). Given the non-systematic nature of media reporting, these records were not treated as comprehensive crash data and were not used for statistical modelling. Instead, they served as contextual triangulation, supporting the premise of persistent operational vulnerability and helping to frame the subsequent UAV-based behavioural diagnosis.

3.2. Official Crash Data and Institutional Coverage

Official crash records were obtained from the Dirección General de Tráfico (DGT), the national authority responsible for road safety on the A-66 motorway. The dataset refers to crashes georeferenced to the A-66 mainline and its immediate influence area in the vicinity of Junction 50 for the period 2015–2024, distinguishing injury crashes (fatalities and/or injuries) and property-damage-only crashes.

An equivalent request was made for the upper road network managed by the Municipality of Mieres (local road overpass and associated junction approaches). However, crash records for the municipal network were not made available. As a result, crash-based evidence in this study is limited to the motorway segment. The crash statistics are, therefore, used to characterise safety outcomes on the A-66 adjacent to the interchange and to support the interpretation of operational mechanisms discussed later, rather than to quantify crash risk at the at-grade junctions themselves.

3.3. UAV Data Collection and Observation Design

Aerial traffic observation was carried out on 3 April 2024 at Junction 50 of the A-66 in Mieres. Two one-hour video datasets were recorded to capture peak operational conditions: 09:00–10:00 (morning) and 14:00–15:00 (early afternoon). These periods were selected based on preliminary flow information and local observations indicating high demand and higher interaction intensity at the site.

The observation windows were not selected as a random sample of annual traffic conditions but rather as critical periods for operational diagnosis. This approach is consistent with standard traffic-engineering practice, where intersection performance is commonly assessed under peak-hour or peak-period conditions. Prior to the UAV campaign, hourly traffic profiles from the nearest representative permanent counting station of the Spanish Ministry of Transport network were reviewed. Station O-327-2, located on the same A-66 corridor, was adopted as the reference station because of its proximity and functional similarity to the study section. Its hourly distribution supported that the selected periods corresponded to high-demand intervals within the daily traffic profile. The same reference station was later used for the AADT estimation procedure reported in Appendix A. This information was complemented by local observations, which indicated recurrent queueing and higher interaction intensity during the selected windows. Therefore, the UAV campaign was designed to capture peak-period operating conditions rather than to provide an exhaustive representation of annual temporal variability.

Flights were operated from the Mieres Fire Station, which provided a secure and elevated location adjacent to the interchange, enabling full visual coverage without road closures or traffic management measures. Prior to recording, a visibility and coverage check was performed using available aerial imagery and CAD-based line-of-sight assessment to confirm that all relevant conflict areas, approach lanes and storage sections were within the camera field of view (Figures 4 and 5). Flight scheduling considered weather forecasts to ensure stable capture conditions (light and wind) and to minimise image degradation.

Video was recorded at a constant altitude of 50 m, which ensured a comprehensive view of the junction while preserving sufficient resolution for trajectory extraction and movement classification.



Figure 4. UAV viewpoint and coverage at 50 m altitude. Source: authors' own elaboration.



Figure 5. UAV flight location and observed area coverage. Source: authors' own elaboration.

3.4. UAV Platform and Flight Specifications

Data were recorded using a DJI Mavic Mini (249 g) equipped with a 12 MP camera and 2.7K video capability. Given the device's battery duration (~20 min), continuous coverage of each one-hour observation window was achieved by rotating three batteries consecutively per session. The UAV was operated manually in Visual Line of Sight (VLOS) mode from the Fire Station by a certified operator.

Operational safety procedures were followed in accordance with Spanish UAV regulations applicable at the time of the flight, including pre-flight checks and verification of operational constraints.

3.5. Video Processing, Trajectory Extraction and Derived Indicators

The UAV videos were processed using the GoodVision Video Insights platform to automatically detect, classify and track vehicles within the study area. The processing produced (i) vehicle counts by class (light/heavy), (ii) turning-movement counts by approach and time interval, (iii) origin–destination (OD) matrices for the two observed periods, and (iv) trajectory datasets suitable for spatial analysis.

GoodVision outputs were subjected to a manual visual quality-control and cross-verification procedure before being used for operational interpretation (Figure 6). The extracted trajectories, turning movements and vehicle classifications were checked against the original UAV footage, with particular attention to the movements introduced into SIDRA and to the conflict areas where irregular manoeuvres were observed. Tracks affected by incomplete detection, duplicate detection, occlusion, abrupt path discontinuity or ambiguous movement assignment were excluded from the irregular-manoeuve interpretation.

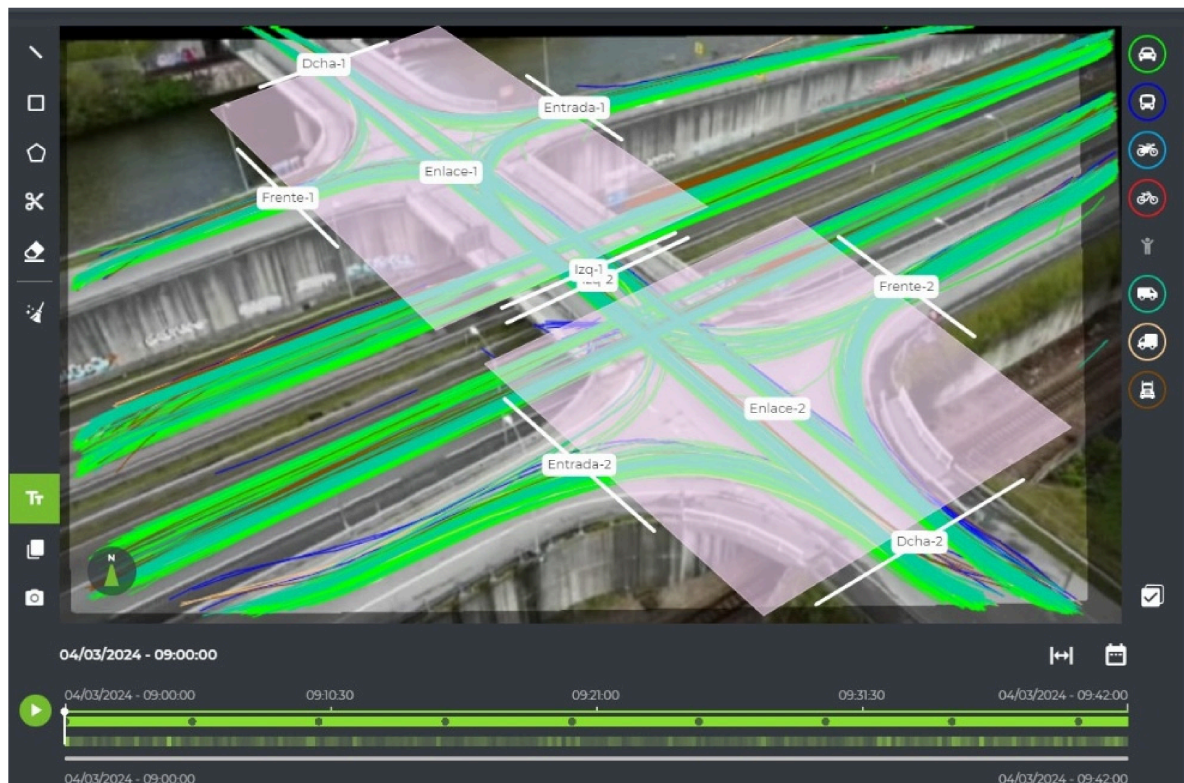


Figure 6. Screenshot of GoodVision Video Insights displaying the scene-description configuration and an overlay of successive vehicle trajectories obtained from automatic detection and tracking in the UAV footage. The different trajectory colours correspond to the default GoodVision visualisation and are used only to distinguish overlapping paths; they do not represent vehicle class, speed, conflict severity or any analytical category used in the study.

The GoodVision-derived data were, therefore, used as visually verified movement-level evidence for trajectory-pattern recognition, heatmap generation and operational modelling. The analysis relied not on centimetre-level trajectory precision but rather on the consistency of observed movement patterns, turning flows and recurrent positioning behaviours.

To support the diagnostic objective, the following outputs were generated from the extracted trajectories:

- Trajectory overlays to visualise path dispersion, lane usage and interactions at decision points.
- Heatmaps of movement density to identify recurrent concentration zones, queue formation areas and potential conflict locations.
- Irregular manoeuvre identification, based on repeated vehicle-positioning and queue-sequence patterns observed in the trajectory overlays and UAV footage (e.g., informal side-by-side queuing at nominally single-lane exits, queue bypassing through adjacent auxiliary areas, and conflicting turns).

Irregular manoeuvres were treated as diagnostic indicators of design–behaviour mismatch rather than as isolated non-compliance events. They were identified through a joint review of the original UAV footage and the corresponding GoodVision trajectory overlays. Four members of the research team reviewed the video material to identify repeated vehicle-positioning patterns inconsistent with the nominal lane configuration of the junction.

A manoeuvre was coded as irregular when at least one of the following operational conditions was observed: (i) two vehicles positioned laterally in parallel at the stop-controlled exit of a nominally single-lane approach; or (ii) a vehicle bypassing the normal queue sequence by using adjacent auxiliary or deceleration space to reach the stop-controlled area ahead of queued vehicles. Events were assigned to Type 1, Type 2 or Type 3 according to the observed sequence of vehicle positioning, queue bypassing and final turning movement. Ambiguous cases, incomplete trajectories or sequences not fully visible in the UAV footage were not used for manoeuvre classification.

For transparency and replicability, the manoeuvre categories were documented using sequential UAV imagery and a classification table linking trigger conditions, observed behaviour and risk mechanism. To assess whether the identified behaviour was concentrated in isolated episodes, the two one-hour UAV recordings were divided into eight 15 min sub-periods. The analysis focused on the S-1 → E-1 movement, where the informal occupation of a second lane was observed. For each subperiod, queue formation at I1 was recorded and S-1 → E-1 movements were classified according to the Type 1–Type 3 configurations defined in Table 1. The resulting counts were checked against the GoodVision OD matrices for the morning and early-afternoon periods. This check was used as an internal robustness assessment, not as a basis for annualising behavioural rates.

Table 1. Operational definition of recurrent irregular manoeuvre types and associated risk mechanism (Type 1–Type 3).

Type	Operational Coding Criterion	Trigger Condition	Driver Behaviour	Risk Generated
Type 1	Two vehicles are laterally aligned at the stop-controlled exit of a nominally single-lane approach and depart towards opposite turning directions	Single-lane layout with apparent excess width	Both vehicles align side by side and turn in opposite directions	Lateral conflict; blocking of opposing flow
Type 2	A following vehicle moves laterally to the right of a stopped or queued lead vehicle and departs before or concurrently with it	Lead vehicle indicates left turn; long queue builds	Second vehicle bypasses and turns right simultaneously	Unexpected path crossing; reduced reaction time
Type 3	A vehicle bypasses at least one queued vehicle through the adjacent deceleration/auxiliary area and reaches the stop-controlled area ahead of the queue	Multiple vehicles queued for left turn	New arrival skips queue and turns right directly	Trajectory interference; visual obstruction for queued vehicles

3.6. Operational Performance Assessment

To complement behavioural evidence with operational performance metrics, extracted turning-movement counts and geometry information were imported into SIDRA INTERSECTION (Figure 7).

The objective was to quantify relative strain across movements and to identify oversaturated conditions consistent with observed queueing and opportunistic behaviour. The analysis focused on standard performance outputs, including: Level of Service (LOS); control delay; capacity utilisation/degree of saturation; and queue and delay patterns.

This performance layer was used diagnostically to triangulate: (i) where demand approaches operational limits and (ii) whether such strain coincides with recurrent irregular manoeuvres and high-density heatmap zones.

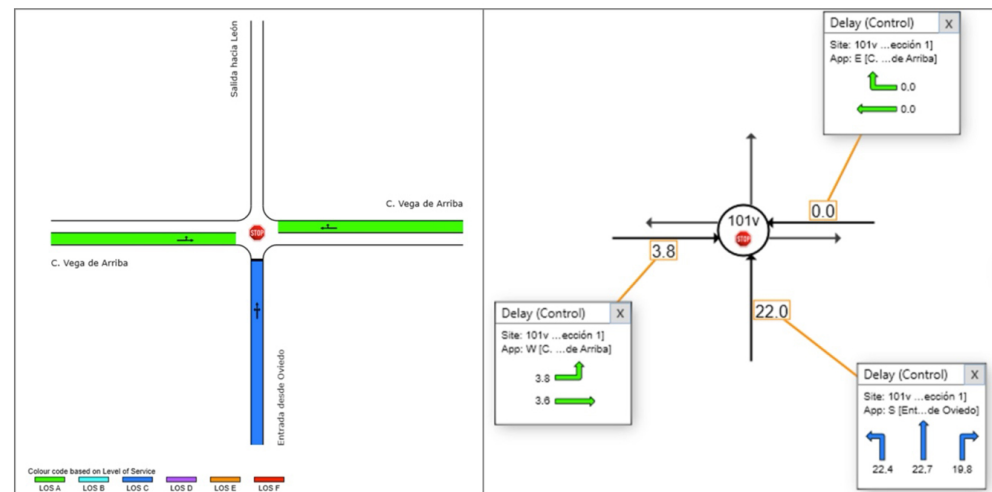


Figure 7. SIDRA INTERSECTION model layout and movement-coding scheme for Intersection I1. The figure is provided to document the model configuration and the coded movements used in the operational assessment; detailed operational results are reported in Section 4.3.

3.7. Regulatory Benchmarking and Compliance Assessment

A regulatory compliance assessment was conducted using the Spanish geometric design standards *Norma 3.1-IC (Instrucción de Carreteras)* as a benchmark for channelisation requirements, turning treatment constraints and auxiliary lane configurations for comparable traffic volumes and design speeds. The aim was not legal adjudication but rather an engineering diagnosis of whether the observed operational reality aligns with current normative expectations—consistent with a Safe System approach in which infrastructure should be self-explaining and forgiving.

Because the standard applies thresholds based on traffic volumes (e.g., channelisation requirements and restrictions on at-grade left turns at specific design speeds), an estimate of AADT was derived from the observed peak-hour intensities and cross-referenced with official Ministry of Transport datasets (2022), yielding an estimated AADT of 5072 vehicles/day for the analysed section (see Appendix A for the AADT estimation procedure).

This estimate was then used to evaluate whether the site’s current turning configuration and the type/length of acceleration–deceleration lanes align with normative requirements.

3.8. Sight-Distance Assessment at Intersection I1 (3D Modelling and Normative Criteria)

A targeted sight-distance assessment was conducted at intersection I1 to evaluate compliance with the Spanish geometric design standard *Norma 3.1-IC*. A 3D model of the approach and surrounding roadside elements was developed to measure the available sight distance from a driver positioned at the stop-controlled exit. Measured sight distances were evaluated against the standard’s reference requirements, including stopping sight distance and the crossing sight distance relevant to the manoeuvre. Three scenarios were defined to represent (i) a single vehicle stopping at a conventional position upstream of the major road, (ii) the recurrent side-by-side configuration observed in the UAV footage (informal parallel positioning), and (iii) a single vehicle stopping at the marked stop line.

3.9. Integrated Analytical Framework and Risk Diagnosis Approach

The methodological design followed a multi-phase analytical framework consistent with Vision Zero and the Safe System approach. The workflow integrates four evidence layers—contextual assessment, UAV-based trajectory evidence, operational performance modelling and regulatory benchmarking—complemented by a targeted sight-distance assessment at I1.

First, the study perimeter and observation windows were defined through a contextual assessment of the junction that considered its functional role within the urban corridor and the applicable design and channelisation requirements. Ancillary information from locally reported serious incidents was used as contextual triangulation to support the premise of persistent operational vulnerability, without treating media records as comprehensive crash data or using them for statistical inference.

Second, UAV flights were conducted to capture the junction's operational dynamics during high-demand periods, and the resulting video was processed in GoodVision to obtain vehicle trajectories, classified volumes, turning-movement counts, origin–destination patterns, and recurrent irregular manoeuvres. Third, extracted flow data and geometry were used in SIDRA INTERSECTION to derive operational performance indicators (e.g., LOS, delay measures and capacity utilisation), enabling identification of movements operating under strain and susceptible to queue spillback and interaction intensification. Fourth, the observed behaviours and operational conditions were assessed against current Spanish geometric design standards (Norma 3.1-IC), including channelisation, turning treatment, auxiliary lane provision and a targeted sight-distance check at the stop-controlled exit of I1.

The four layers were combined through a simple triangulation rule: a movement or area was flagged as critical when (a) trajectory evidence showed recurrent irregular manoeuvres or concentrated interaction patterns, (b) SIDRA outputs indicated high utilisation or unstable queueing for the corresponding movement, and/or (c) the observed configuration deviated from the expectations derived from Norma 3.1-IC for comparable traffic volumes and design conditions. The resulting outputs were (i) a ranked set of critical movements, (ii) mapped locations where interaction density and queue spillback concentrate, and (iii) a set of candidate design/operational issues expressed as design–behaviour mismatches.

The integrated workflow is summarised in Figure 8.



Figure 8. Integrated workflow for Vision Zero-oriented risk diagnosis combining UAV-based trajectory analysis (GoodVision), operational performance modelling (SIDRA INTERSECCION) and regulatory benchmarking (Norma 3.1-IC), supplemented by descriptive crash context.

4. Results

4.1. Traffic Volume and Directional Flow Patterns

UAV-based observation provided turning-movement and trajectory data for two one-hour periods representing morning (09:00–10:00) and early-afternoon (14:00–15:00) peak conditions. Across both sessions, 3268 vehicle movements were recorded within the study perimeter, distributed between the two analysed intersections (I1 and I2).

At I1, 736 vehicles were observed in the morning and 820 in the afternoon (+11.4%). Traffic composition was dominated by light vehicles (>95%), with a small heavy-vehicle component (34 in the morning; 20 in the afternoon). The most frequent origin–destination movement was S-1 → O-1, increasing from 310 vehicles (morning) to 394 vehicles (afternoon), consistent with the corridor’s dominant directional pattern.

At I2, volumes were substantially higher, with 1152 vehicles in the morning and 1560 in the afternoon (+35.4%). The highest demand was concentrated at approaches O-2 (inbound) and S-2 (outbound), which together accounted for >60% of the movements during the afternoon peak. As in I1, light vehicles represented the overwhelming majority of the observed traffic.

Queueing was directly observable in the UAV footage at I1, particularly near the exit zone. In both observation windows, vehicle accumulation occurred at the stop-controlled area, with visibly longer queues in the afternoon session. Figure 9 illustrates representative snapshots of these conditions.

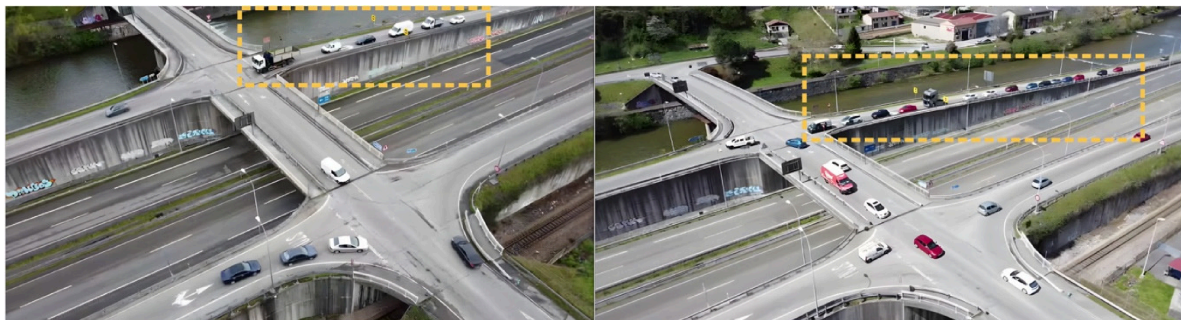


Figure 9. Queuing at intersection I1 during morning and early-afternoon peak hours (3 April 2024). Source: UAV imagery.

4.2. Recurrent Irregular Manoeuvres and Design–Behaviour Mismatch

Trajectory evidence extracted with GoodVision revealed recurrent irregular manoeuvres that are not represented by conventional count-based datasets and are not explicitly anticipated by the current junction layout. Observed patterns included (i) informal side-by-side queuing at nominally single-lane, stop-controlled exits; (ii) concurrent opposing turns originating from the same effective departure space; and (iii) queue bypassing using adjacent deceleration/auxiliary areas.

At I1, a repeated configuration involved two vehicles aligning laterally at the end of the access ramp: one preparing for a left turn and the other for a right turn. Although the exit is formally configured as a single-lane stop-controlled approach, the available transverse width—intended for shoulder provision and turning accommodation—was frequently interpreted as enabling two simultaneous turning paths. This produced parallel queuing and concurrent departures, increasing the likelihood of lateral conflict and trajectory interference with opposing traffic.

At I2, queue bypassing was observed during the afternoon peak, with vehicles using adjacent deceleration lanes or buffer areas to advance past standing queues. While this

behaviour reduces individual delay, it increases trajectory unpredictability and reduces reaction margins for other users, particularly where visibility and guidance cues are limited.

The recurrence of these behaviours in both time windows suggests a systematic design-behaviour mismatch rather than isolated non-compliance events. Following the operational coding criteria described in Section 3.5, three recurrent manoeuvre types (Type 1–Type 3) were retained for diagnostic interpretation. These types are summarised in Table 1, while representative sequential examples are shown in Figure 10. To assess whether these behaviours were concentrated in isolated episodes, the S-1 → E-1 movement was also examined across eight 15 min subperiods. The resulting distribution of queue formation and Type 1–Type 3 configurations is reported in Table 2.

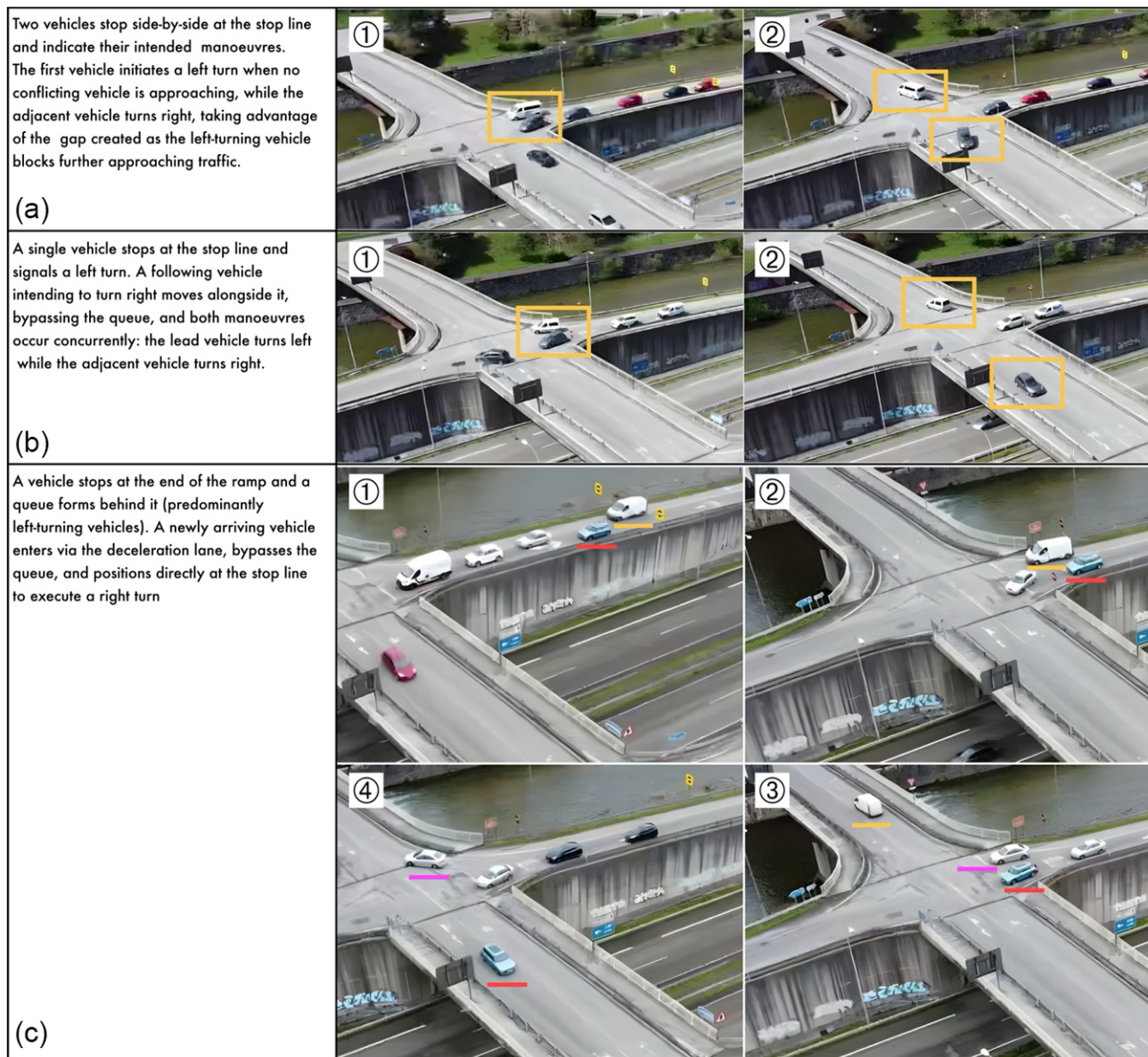


Figure 10. Sequential UAV snapshots illustrating recurrent irregular manoeuvres at the stop-controlled exit: (a) Type 1—side-by-side stopping with simultaneous left and right turns; (b) Type 2—right-turn vehicle bypasses the queue and turns concurrently with a left-turning vehicle; (c) Type 3—queue bypass via the deceleration lane to perform a right turn. Circled numbers indicate the temporal sequence within each manoeuvre. Orange boxes highlight the vehicles involved in the manoeuvre, while coloured line markers are used to distinguish individual vehicles across successive frames; they do not represent vehicle class, speed or conflict severity. Source: UAV imagery (3 April 2024).

Table 2. Temporal distribution of S-1 → E-1 movements by observed manoeuvre configuration across 15-min subperiods.

Observation Period	Subperiod	Queue at I1	Type 1	Type 2	Type 3	Total S-1 → E-1 Movements
AM	09:00–09:15	Yes	2	6	4	12
AM	09:15–09:30	Yes	4	2	8	14
AM	09:30–09:45	Yes	2	4	10	16
AM	09:45–10:00	Yes	2	2	4	8
PM	14:00–14:15	Yes	4	6	10	20
PM	14:15–14:30	Yes	2	4	4	10
PM	14:30–14:45	Yes	2	6	18	26
PM	14:45–15:00	Yes	4	2	8	14
Total			22	32	66	120

The 15 min segmentation shows that the observed mechanism was not confined to a single episode. Queue formation at I1 was present in all eight subperiods. The three manoeuvre configurations were also observed in every subperiod. Across the two peak-period recordings, 120 S-1 → E-1 movements were classified: 22 as Type 1, 32 as Type 2 and 66 as Type 3. These values are consistent with the OD matrices obtained from GoodVision, which recorded 50 S-1 → E-1 movements in the morning period and 70 in the early-afternoon period.

Although the relative frequency of each type varied between subperiods, the same behaviour remained associated with the same decision point and geometric condition. This supports the interpretation of the mechanism as recurrent within the observed peak-period dataset rather than as an isolated incidental observation.

4.3. Operational Performance Indicators

Turning-movement counts derived from the UAV data were used as inputs for SIDRA INTERSECTION to quantify operational performance at the movement level. The analysis focused on standard outputs: Level of Service (LOS), control delay, capacity utilisation/degree of saturation, and queue-related indicators where available.

At I1, the most critical movement was the left turn S-1 → O-1, reaching >90% capacity utilisation in the afternoon peak. This movement exhibited an average control delay of 38 s/veh and was classified as LOS E, which indicates substantial operational strain and unstable flow conditions. The corresponding right-turn movement—while less congested—showed intermittent interference consistent with the observed informal side-by-side queuing behaviour.

At I2, despite a more distributed demand, the westbound movement O-2 → S-2 exceeded 95% saturation in the afternoon peak, with delays >40 s/veh and LOS in the E–F range. Several additional movements operated at LOS D or worse, particularly where merging and turning occur under constrained geometry.

Overall, SIDRA outputs indicate that the selected movements are operating close to their functional limits during peak demand, consistent with the queueing and trajectory interference patterns observed in the UAV footage.

4.4. Visualization of Trajectory Patterns and Congestion Zones

Trajectory reconstruction and spatial aggregation enabled a complementary diagnostic view of movement concentration and path dispersion. Individual trajectories were rendered and aggregated into movement-density heatmaps (Figures 11 and 12), which highlighted recurrent concentration zones, queue formation areas and locations where paths overlap at decision points.

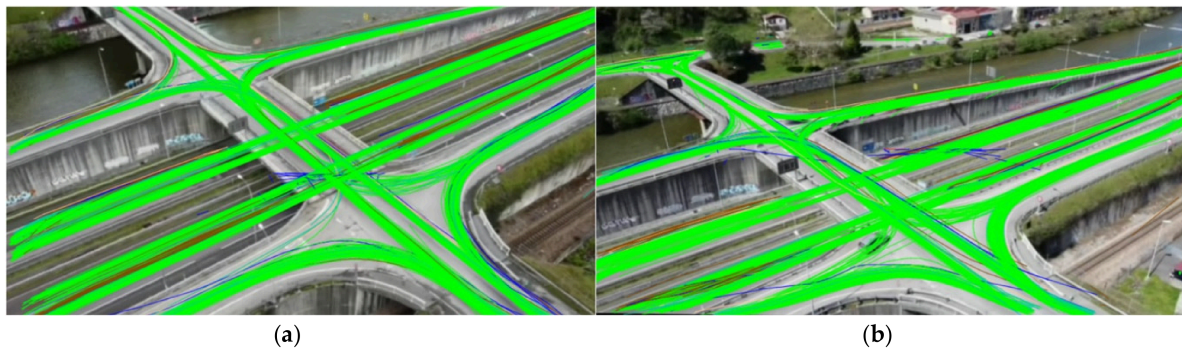


Figure 11. Trajectory overlays derived from UAV video at intersection I1: (a) morning peak (09:00–10:00) and (b) early-afternoon peak (14:00–15:00). Each line represents the trajectory of a detected vehicle movement. The different colours correspond to the default GoodVision visualisation and are used only to distinguish overlapping trajectories; they do not represent vehicle class, speed, conflict severity or any analytical category used in the study. Source: authors' processing of GoodVision outputs.

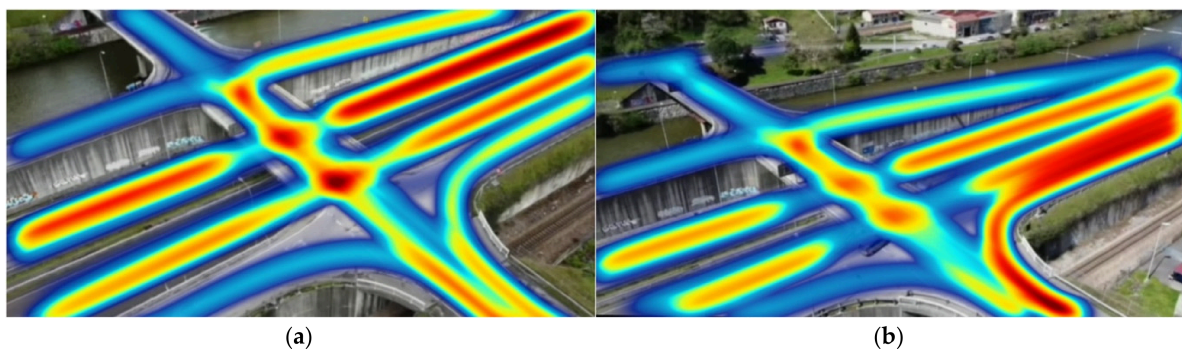


Figure 12. Movement-density heatmaps at intersection I1: (a) morning peak (09:00–10:00) and (b) early-afternoon peak (14:00–15:00). The colour scale represents relative trajectory density: cooler colours indicate lower concentrations of vehicle trajectories, whereas warmer colours indicate higher concentrations. The colours do not represent vehicle speed, vehicle class or conflict severity. Source: authors' processing of GoodVision outputs.

At I1, the trajectories confirmed the dominance of S-1 → O-1 and showed converging paths near the exit zone. In the afternoon peak, lateral dispersion increased at the decision point, consistent with the informal side-by-side alignment described in Section 4.2. This area coincided spatially with the movement identified as most strained in the SIDRA analysis.

At I2, the trajectories highlighted the predominance of flows entering from O-2 and exiting towards S-2, particularly in the afternoon peak. Dispersion in the N-2 → O-2 movement suggests inconsistent lane selection and potential ambiguity in guidance cues. Heatmaps showed concentrated flow corridors in areas where operational performance was classified as LOS E/F.

4.5. Crash Record on the A-66 Segment Adjacent to the Interchange (2015–2024)

According to the DGT records for 2015–2024, a total of 11 injury crashes were registered on the A-66 in the vicinity of Junction 50. A marked directional imbalance was observed: 10 injury crashes occurred in the increasing direction, corresponding to the carriageway where the motorway exit towards the analysed interchange is located, whereas 1 injury crash was recorded in the decreasing direction.

Regarding crash type, rear-end collisions predominated among the injury crashes, consistent with sudden speed drops and low-speed/standing queues within a high-speed

environment. Additional injury crashes included run-off-road events ($n = 4$) and one pedestrian-involved crash ($n = 1$). With respect to temporal distribution, all but one injury crash occurred on weekdays. Most injury crashes were recorded under non-severe weather conditions (e.g., fair weather or light drizzle), with only one event under heavy rain and none under strong wind conditions.

In the same period, 29 property-damage-only crashes were also recorded for the same motorway location; however, detailed descriptors are not systematically available for these events within the consulted dataset. The official DGT report is provided for traceability in Appendix C.

4.6. Regulatory Benchmarking Against Norma 3.1-IC

A regulatory benchmarking assessment was conducted using Norma 3.1-IC (Instrucción de Carreteras) to evaluate whether the observed configuration aligns with current design expectations for comparable demand levels and design conditions. The objective was an engineering diagnosis of potential design–operation misalignment, not legal adjudication.

According to Norma 3.1-IC, intersections exceeding specified traffic thresholds require channelisation; for design speeds of 40 km/h, the standard restricts at-grade left-turn manoeuvres at higher traffic volumes and specifies requirements for auxiliary lanes and deceleration wedges (Figure 13). In the analysed section (Vega de Arriba), the estimated AADT = 5072 veh/day (derived from UAV counts and referenced against the Ministry of Transport 2022 dataset) exceeds the relevant thresholds for unchannelised at-grade turning and bifurcated configurations under the stated design conditions.

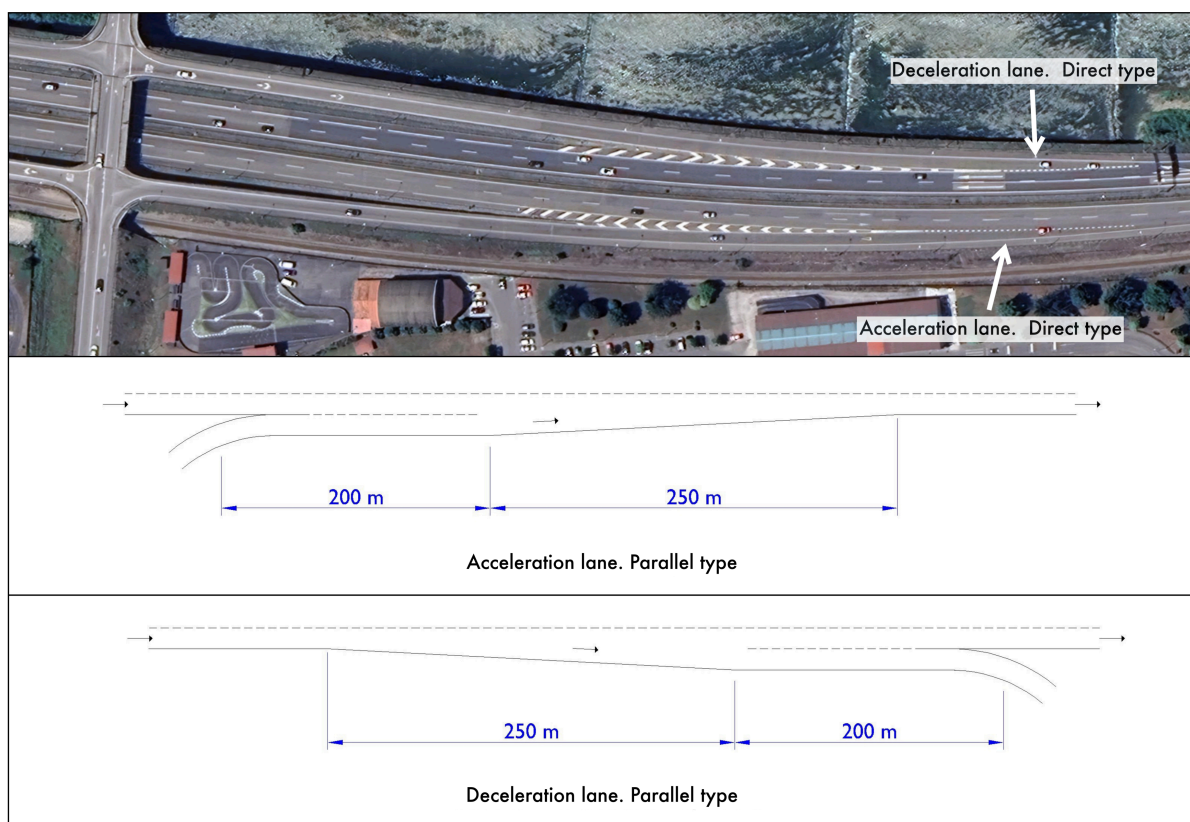


Figure 13. Existing direct-type acceleration/deceleration lanes observed at Junction 50 (A-66) contrasted with the parallel-type layouts required by the Spanish geometric design standard Norma 3.1-IC for the applicable design speed (schematic adapted from Instrucción de Carreteras, Norma 3.1-IC, Ministerio de Transportes).

In addition, the acceleration/deceleration lane configuration differs from the current normative prescriptions. The standard prohibits direct-type deceleration lanes at the design speed applicable to this section and does not permit direct-type acceleration lanes, requiring parallel-type configurations to provide adequate diverging/merging lengths. Field observation confirms the presence of direct-type elements. The existing taper length of the parallel-type deceleration wedge is approximately 75 m, which is substantially below the 250 m reference indicated by the standard—even under a hypothetical assumption of acceptability of a direct-type arrangement.

4.7. Sight-Distance Benchmarking at I1

The 3D sight-distance assessment indicates that the available sight distance at the stop-controlled exit of intersection I1 is constrained by roadside elements and falls below the reference requirements of Norma 3.1-IC. For a posted speed of 50 km/h, the standard specifies a stopping sight distance (D_p) of 52 m and a crossing sight distance (D_c) of 97 m for the manoeuvre conditions at this junction.

In Scenario 1 (single vehicle stopping approximately 3 m upstream of the edge of the major road), sight to the left is limited by the bridge railing (15 m) and sight to the right by the guardrail (32 m), both well below D_p and D_c . In Scenario 2 (informal side-by-side positioning observed in the UAV footage), the adjacent right-turning vehicle obstructs right-side visibility, limiting the available sight distance to 23.5 m even when the left-turning vehicle creeps forward. In Scenario 3 (single vehicle stopping at the marked stop line), the available sight distance remains constrained to 20 m to the left and 37.5 m to the right. Across the three scenarios, the measured values are substantially lower than the normative reference distances, indicating that the stop-controlled exit operates under persistently limited sight conditions (Figure 14).

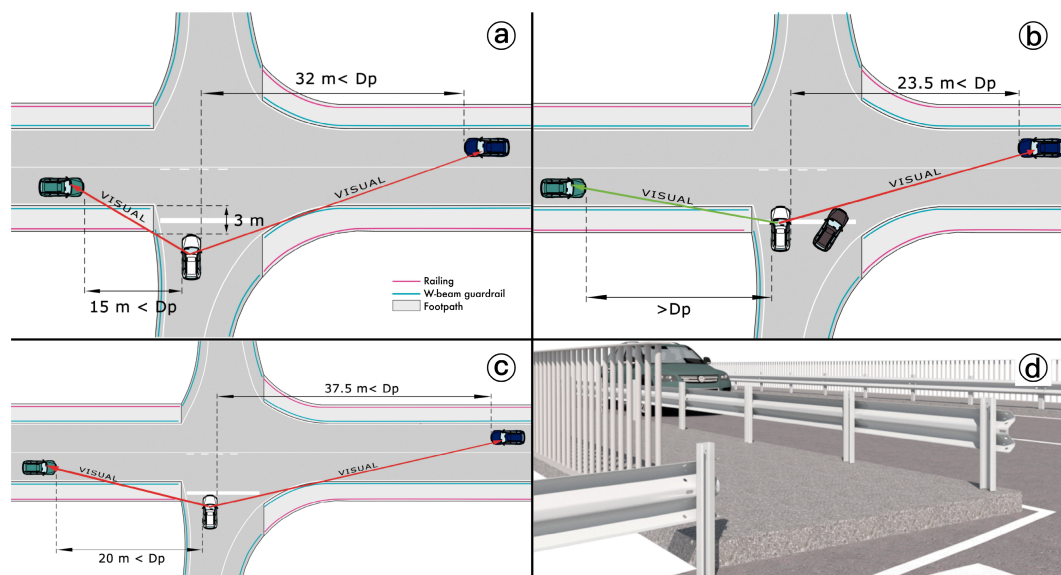


Figure 14. Sight-distance assessment at the stop-controlled exit of intersection I1 under three scenarios (a–c) and 3D model view (d). Measured available sight distances are below the stopping sight distance required by Norma 3.1-IC for $V = 50$ km/h ($D_p = 52$ m) and are also insufficient relative to the required crossing sight distance ($D_c = 97$ m). Scenario 1 shows a single vehicle stopped approximately 3 m upstream of the major road, with sight constrained by the bridge railing (left) and the W-beam guardrail (right). Scenario 2 represents the recurrent side-by-side configuration observed in UAV footage, where the adjacent vehicle further restricts right-side visibility. Scenario 3 shows a single vehicle stopped at the marked stop line. Panel (d) illustrates the 3D model highlighting the occluding effect of the bridge railing.

The three scenarios were represented using passenger-car positions because light vehicles accounted for more than 95% of the observed traffic at I1 and because the recurrent side-by-side configuration was observed almost exclusively among passenger cars. During the UAV survey, heavy vehicles such as trucks or buses occupied a larger transverse envelope and did not generate the same informal two-vehicle parallel queue at the stop-controlled exit. In practice, their presence tended to prevent, rather than reproduce, the side-by-side configuration analysed in Scenario 2. In addition, drivers of heavy vehicles have a higher eye position than passenger-car drivers, which may reduce the obstructing effect of low roadside elements such as railings and containment systems on their own sight line. Therefore, the sight-distance assessment focuses on the vehicle class and positioning pattern most directly associated with the observed irregular manoeuvre. Heavy vehicles may still be relevant as occluding objects for other road users in a project-level design review, but they were not the dominant mechanism associated with the recurrent irregular behaviour documented in this study.

5. Discussion

5.1. Interpretation of Results and Diagnostic Insights

The results converge on a practical diagnosis for Junction 50: recurrent behaviour concentrates at a small number of decision points and is closely tied to the way the layout is read in real time. What stands out in the UAV footage is not occasional non-compliance but rather repetition. This interpretation is supported by the 15 min segmentation, which shows that queue formation and the three manoeuvre configurations were present across all subperiods of the observed peak-period dataset. Side-by-side alignment at a nominally single-lane stop line, concurrent turning paths, and queue-bypass manoeuvres appear in both observation windows and recur in the same micro-locations.

A plausible driver of these patterns is spatial ambiguity. The exit is formally single-lane, yet the available transverse width—including a 2.5 m shoulder specified for motorway exit sections in Norma 3.1-IC—can be read as a second usable path when markings and physical guidance are weak. In that setting, functional safety space is treated as carriageway, and a single-lane control condition effectively becomes two competing trajectories.

Complementary geometric evidence is provided by the sight-distance assessment at I1. The 3D-based analysis shows that the available sight distances at the stop-controlled exit are below the Norma 3.1-IC reference values for $V = 50$ km/h ($D_p = 52$ m; $D_c = 97$ m) across all tested scenarios. Sight distance is constrained by the bridge railing and guardrail, and in the side-by-side configuration, the adjacent vehicle further restricts right-side sight, which is consistent with forward creeping, parallel positioning and concurrent turning at this interface.

Operational conditions matter as well. Where SIDRA indicates high utilisation and unstable queues (LOS E–F), the footage shows more opportunistic positioning: late lateral shifts, queue bypassing through the adjacent auxiliary space, and simultaneous departures that compress reaction time. This does not establish crash causation, but it does clarify how demand-capacity strain and short storage/merge areas can intensify interactions and increase exposure to conflict-prone configurations at precisely the locations where the geometry is the least self-explaining. This interpretation is further triangulated using official crash data for the adjacent motorway segment.

Complementary evidence is provided by the official crash record for the adjacent A-66 segment (Appendix C). In 2015–2024, 11 injury crashes were recorded in the vicinity of Junction 50, with a pronounced directional imbalance: 10 occurred in the increasing direction, i.e., the carriageway hosting the exit towards the analysed interchange. Although these crashes are not located at the at-grade junctions themselves, the asymmetry is com-

patible with recurrent spillback when the ramp storage is exhausted. Under sustained oversaturation, the exit queue may occupy the full ramp width and propagate upstream to the motorway mainline, where stopped or very low-speed vehicles constitute an unexpected obstacle in a high-speed environment. The predominance of rear-end collisions in the injury-crash sample is consistent with abrupt speed reductions associated with queuing dynamics. In addition, 29 property-damage-only crashes were recorded for the same motorway location over the study period; however, detailed descriptors are not systematically available for these events in the consulted dataset. Causal attribution cannot be demonstrated with the available datasets, but the crash pattern supports the plausibility of the operational mechanism identified in the UAV-based observations.

Finally, the regulatory benchmarking against Norma 3.1-IC supports the interpretation that the junction is a legacy configuration operating outside contemporary design expectations for comparable demand. The mismatch is not a purely formal issue. In Safe System terms, when the layout fails to communicate permitted paths and constraints unambiguously, the burden of safety shifts towards individual judgement. The behavioural patterns documented here are consistent with that shift.

The proposed framework should, therefore, be interpreted within the logic of Vision Zero and the Safe System approach. Its purpose is not to demonstrate that the site is statistically worse than a reference population of junctions, nor to estimate crash probability directly. Rather, it seeks to identify correctable system deficiencies before severe outcomes accumulate. In the present case, the safety relevance of the diagnosis is supported by the convergence of documented crashes in the functional environment of the interchange, recurrent non-standard manoeuvres, movement-level operational strain, insufficient sight distance and inconsistencies with current geometric design standards. From a Vision Zero perspective, this convergence is meaningful because infrastructure should anticipate ordinary human error and prevent ambiguous layouts from producing conflict-prone interactions. Formal surrogate safety indicators, such as Post-Encroachment Time or Time-to-Collision, would provide an additional quantitative layer for estimating conflict severity; however, their calculation is beyond the scope of the present diagnostic demonstration and would require longer observation periods and fully validated microscopic trajectories.

5.2. Comparison with Related Studies and Methodologies

UAV-based traffic analysis has gained traction because it captures intersection dynamics that are difficult to observe with fixed cameras or aggregate count stations. Reviews underline this flexibility and the ability to visualise conflict points and interactions with high spatial resolution [18]. Studies have also demonstrated the feasibility of extracting trajectories and identifying anomalous behaviour from UAV footage under real conditions [19,20].

The contribution of the present study sits in the workflow integration. Trajectory extraction is treated as a means to an end: a site-level diagnostic that links behavioural evidence to movement-level operational strain (SIDRA INTERSECTION) and to an explicit normative benchmark (Norma 3.1-IC). That combination reflects how retrofit decisions are often made in practice—through a mix of observed operation, performance constraints and standards-based justification—especially in constrained junctions where redesign options are limited.

In Spain, long-run safety gains have been associated with institutional reforms and policy measures [8,9]. This case complements that picture by showing how locally inherited geometries can remain in service while producing persistent interpretability problems under current demand. The point is not that standards alone determine safety outcomes

but rather that standards provide a structured way to articulate why certain design features become problematic once operational conditions and user expectations evolve.

5.3. Limitations

The evidence base is limited to two one-hour observation windows on a single week-day. The dataset, therefore, does not capture day-to-day variability, seasonal effects or special-event conditions, and the observed behavioural patterns should not be interpreted as annualised or statistically exhaustive estimates. However, the observation windows were not selected arbitrarily. They were chosen after a preliminary demand-screening process based on hourly traffic profiles from the nearest representative permanent counting station and local observations, with the aim of capturing high-demand operating conditions in which queueing, interaction density and design-behaviour mismatch were most likely to become observable. The dataset is, therefore, suitable for the narrower purpose of peak-period operational diagnosis, although not for a complete temporal characterisation of the junction. Observations were also made under favourable weather and visibility; behaviour and lane interpretation may differ under rain, fog, low light or degraded markings.

Trajectory extraction depends on computer-vision performance. Although GoodVision outputs were visually checked against the original UAV footage, a full independent validation of trajectory-position error was not performed, and no ground-control trajectory dataset was available. Even with post-processing checks, residual tracking errors can occur due to occlusions, close headways in queues and classification uncertainty. Consequently, the GoodVision outputs should be interpreted as supporting movement-level diagnosis, trajectory-pattern recognition and operational modelling rather than precise microscopic trajectory reconstruction. In addition, SIDRA outputs depend on modelling assumptions (e.g., saturation flows and gap-acceptance settings). In this study, the model is used to characterise relative strain and identify movements close to saturation rather than to predict absolute delays; sensitivity checks would nevertheless strengthen the ranking of critical movements.

Formal surrogate safety indicators, such as Post-Encroachment Time or Time-to-Collision, were not calculated in this study. The results should, therefore, be interpreted as a proactive diagnosis of latent safety vulnerability and correctable design-behaviour mismatch rather than as a quantitative estimation of crash probability or conflict severity. Future applications of the framework should incorporate such indicators when the objective is to quantify conflict severity from validated microscopic trajectories.

The sight-distance assessment was based on passenger-car scenarios. This choice reflected the observed traffic composition at I1, where light vehicles represented more than 95% of the flow, and the fact that the recurrent side-by-side queueing pattern was observed almost exclusively among passenger cars. Heavy vehicles were not modelled explicitly. During the UAV observations, their larger transverse envelope generally prevented the informal parallel queue configuration rather than generating it. In addition, their higher driver eye position may reduce the effect of low roadside obstacles on their own sight line. Nevertheless, heavy vehicles may act as occluding objects for other users and should be considered in future project-level assessments.

The regulatory assessment is presented as engineering benchmarking against Norma 3.1-IC. Retrofit feasibility, transitional criteria and administrative practice can affect how road authorities apply standards to existing infrastructure; the compliance discussion should, therefore, be read as diagnostic context rather than legal adjudication.

Crash-based evidence is subject to institutional coverage constraints. Official records were available for the A-66 motorway segment through the DGT, whereas equivalent crash data for the upper municipal network could not be accessed. Accordingly, the crash record

is reported descriptively for the motorway location and cannot be used to estimate crash risk at the at-grade junctions. Property-damage-only crashes are available only as aggregate counts in the consulted extract, without a typological breakdown.

5.4. Implications for Practice and Governance

The most immediate implication is geometric: the stop-controlled exit and taper areas where lateral alignment and concurrent turning occur should be treated as priority locations for ambiguity reduction. Clearer lane markings, channelisation elements, and the physical delineation of shoulder vs. carriageway can prevent the “two-lane reading” of a single-lane control condition. Where queue bypassing uses auxiliary space, signing and marking should be reviewed so that functional space is not interpreted as an overtaking opportunity.

The diagnostic results can be translated into a limited set of project-level engineering implications. Table 3 does not define a final design solution but rather identifies the elements that should be addressed in a subsequent road-design study.

Table 3. Engineering implications derived from the diagnostic results.

Location	Finding from the Diagnostic Analysis	Engineering Implication
I1 stop-controlled exit	The exit operates as a nominal single-lane approach, but the available transverse width is repeatedly interpreted as space for two vehicles in parallel.	The departure area should be redesigned or marked so that only one queueing position is legible. The shoulder/auxiliary width should be clearly excluded from the traffic lane by hatching, edge marking or physical/semi-physical delineation.
I1 stop line and sight envelope	Available sight distance is below the Norma 3.1-IC reference values for both stopping and crossing conditions.	A project-level review should assess whether railings, containment systems or other roadside elements can be modified, lowered, relocated or replaced to improve the sight envelope.
I2 auxiliary/deceleration area	Vehicles use adjacent auxiliary space to bypass queues and reach the stop-controlled area ahead of queued vehicles.	The auxiliary area should be redefined so that it cannot be read as an overtaking or bypass lane. Markings, chevrons, edge lines or delineators should be used to close non-operational space to traffic.
Acceleration/deceleration lane configuration	The existing configuration includes direct-type elements and an approximately 75 m taper, whereas the benchmarking against Norma 3.1-IC indicates the need to review lane type and length; the reference taper length identified in the analysis is 250 m.	The acceleration/deceleration layout should be reassessed against current Norma 3.1-IC criteria. Where feasible, direct-type elements should be replaced by parallel-type layouts and taper/storage lengths should be adjusted to current design requirements.
Ramp storage and spillback towards the A-66	Queuing at the ramp terminal is consistent with the directional imbalance and rear-end crash pattern observed on the adjacent motorway segment.	Storage and discharge conditions at the ramp terminal should be reviewed to reduce the probability of queue spillback towards the mainline carriageway.

These measures should be interpreted as design requirements for subsequent project development rather than as final geometric solutions. Their detailed definition would require topographic survey, swept-path analysis for heavy vehicles, drainage and containment checks, and approval by the responsible road authority.

A second implication concerns operations. Movements exhibiting high utilisation and unstable queues warrant a targeted review of storage, merge/diverge lengths and, where feasible, control strategy adjustments. Reducing spillback and compressive interactions helps curb the conditions under which opportunistic manoeuvres become attractive.

At a governance level, the integrated workflow—UAV observation, trajectory-based spatial diagnosis, movement-level performance modelling and standards benchmarking—provides a practical basis for prioritising retrofit actions in legacy junctions where crash data may be sparse or weakly informative at the micro-scale. That is where Vision Zero’s proactive logic is the most useful: not as a slogan but rather as a criterion for acting on recurring, observable design–behaviour mismatches before severe outcomes accumulate.

6. Conclusions

This study developed and demonstrated a Vision Zero/Safe System-oriented diagnostic workflow to characterise latent safety-vulnerability mechanisms at complex junctions without relying on crash frequency as the primary signal. The framework integrates (i) UAV-based observation, (ii) computer-vision trajectory extraction (GoodVision), (iii) movement-level operational performance modelling (SIDRA INTERSECTION), and (iv) regulatory benchmarking against the Spanish geometric design standard Norma 3.1-IC. The case study at Junction 50 of the A-66 motorway in Mieres (Asturias, Spain) provided an applied setting to test this integrated approach under constrained legacy geometry and peak-demand conditions. Crash records, where available, were used only as contextual evidence to support the interpretation of motorway-adjacent vulnerability mechanisms.

This case study supports four practical findings. UAV-derived trajectories show recurrent non-standard manoeuvres—most notably informal side-by-side queuing and concurrent opposing turns at a nominally single-lane, stop-controlled exit, along with queue bypassing via adjacent auxiliary areas. Their recurrence across the eight 15 min subperiods supports the interpretation of a systematic adaptation to ambiguous geometric cues rather than isolated non-compliance within the observed peak-period dataset.

Furthermore, movement-level performance modelling (SIDRA INTERSECTION) indicates that critical movements operate close to capacity during peak demand (LOS E–F), consistent with the observed queueing and trajectory interference. The geometric and normative assessment further indicates a misalignment with current design expectations (Norma 3.1-IC), including acceleration/deceleration lane type and length, turning/channelisation criteria for the estimated demand level, and insufficient sight distance at the stop-controlled exit relative to the reference stopping and crossing distances (D_p and D_c).

Finally, official crash records for the adjacent A-66 segment (2015–2024) report 11 injury crashes, with a pronounced directional imbalance (10 in the increasing direction, associated with the exit towards the analysed interchange). Although these crashes are not located at the at-grade junctions themselves, the pattern is compatible with recurrent queue spillback when the exit-ramp storage is exhausted and aligns with the queueing dynamics observed in the UAV footage.

The main contribution is methodological. The workflow shows how high-resolution behavioural evidence can be translated into intervention-relevant outputs—ranked critical movements, mapped concentration zones, and explicit design–behaviour mismatches—using a transparent triangulation rule across observation, operational strain and normative benchmarks. This supports proactive prioritisation in Vision Zero governance contexts, particularly for legacy junctions where redesign options are constrained and crash-based signals may be sparse, delayed or weakly diagnostic at the micro-scale.

This study's scope remains bounded by the limited temporal coverage (two one-hour windows on a single day) and by uncertainties inherent to computer-vision tracking and model assumptions in performance estimation. Extending observation across additional days and conditions, reporting trajectory-quality metrics systematically, and incorporating formal surrogate safety indicators such as Post-Encroachment Time or Time-to-Collision would strengthen the evidential base where the objective is to quantify conflict severity. In the present study, the contribution lies in demonstrating how UAV-based behavioural evidence, operational performance, sight-distance assessment and regulatory benchmarking can be combined to identify latent safety vulnerability and correctable design–behaviour mismatches before severe outcomes accumulate.

Within these limits, the proposed workflow provides a transferable template for structuring Vision Zero-oriented evidence in a form usable for design review, retrofit prioritisation and proactive safety governance at complex legacy junctions. Future applications

at additional junctions would help assess transferability, while the present case illustrates the value of site-level diagnosis for identifying correctable design–behaviour mismatches before severe outcomes accumulate.

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Appendix A. AADT Estimation

To ensure that the traffic volumes obtained from the peak-hour field measurements are representative on an annual scale, a calibration procedure was applied based on the traffic patterns recorded by the network of permanent counting stations operated by the Spanish Ministry of Transport and Sustainable Mobility. This procedure converts the on-site measurements into an estimate of Average Annual Daily Traffic (AADT), accounting for both the hourly distribution of traffic and seasonal variability.

Appendix A.1. Calibration and Traffic Counting Stations

At the time the measurements were carried out, the most recent official traffic map available corresponded to the year 2022.

The two stations closest to the study area are:

- Station O-327-2, located north of the study area, at km point (PK) 45.62 on the A-66 motorway.
- Station O-54-5, located south of the study area, at km point (PK) 51.32 on the same motorway.

Considering the function of the link under study, its position within the national road network, and the similarity in mobility patterns, station O-327-2 was deemed the most representative of the behaviour of the analysed intersection. For this reason, its hourly percentages were adopted as the reference for the calibration process.

Appendix A.2. Hourly Traffic Distribution

Using station O-327-2, the hourly percentages for an average Wednesday were obtained. These percentages represent the share of total daily traffic occurring in each hour of the day. For example, at 09:00, 6.89% of the daily traffic is recorded in the Mieres-bound direction and 7.35% in the Oviedo-bound direction (Table A1).

Table A1. Average Wednesday Hourly Traffic Distribution by Direction at Traffic Counting Station O-327-2 (%).

Time (h)	Mieres Direction (%)	Oviedo Direction (%)
0:00	0.50	0.52
1:00	0.42	0.43
2:00	0.18	0.19
3:00	0.26	0.26
4:00	0.36	0.38
5:00	1.08	1.17
6:00	2.37	2.55
7:00	5.48	5.76
8:00	7.92	6.64
9:00	6.89	7.35
10:00	5.68	5.61
11:00	5.16	5.04
12:00	4.98	5.00
13:00	5.56	5.61
14:00	6.57	6.80
15:00	7.56	7.57
16:00	6.19	6.09
17:00	6.44	6.39
18:00	6.76	6.62
19:00	5.93	6.00
20:00	4.85	4.92
21:00	3.66	3.84
22:00	3.38	3.38
23:00	1.84	1.88
AADT (approx.)	13,723	14,873

Appendix A.3. Calculation of Relative AADT

For each counted time period, a relative AADT was estimated using the following expression:

$$AADT_{relativa} = \frac{\text{Peak - hour measured volume}}{\text{Hourly percentage}}$$

This equation estimates the equivalent daily traffic volume corresponding to the observed peak-hour flow, assuming that the observed period is representative of the whole day according to the reference hourly pattern.

The resulting values can be seen in Table A2.

Table A2. Relative AADT estimates by direction based on peak-hour counts and the hourly traffic distribution of reference station O-327-2.

AM (9:00)	Count (veh/h)	Relative AADT (veh/Day)
Eastbound	158	2150
Westbound	216	3135
PM (14:00)	Count (veh/h)	Relative AADT (veh/day)
Eastbound	158	2150
Westbound	216	3135

These results correspond to a typical Wednesday and, therefore, do not yet represent the annual AADT.

Appendix A.4. Seasonal and Weekly Adjustment

To convert the AADT corresponding to a Wednesday in April (the month when the field counts were carried out) into an annual AADT, an adjustment factor was derived from data from station O-327-2. At this station, the AADT is 24,448 veh/day. The average daily traffic for all months and days of the year can be obtained from the table below; specifically, the value for a Wednesday in April is 29,805 veh/day (Table A3).

Table A3. Average daily traffic by month and day of the week at reference counting station O-327-2.

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	26,332	25,860	25,994	23,465	27,222	18,965	15,714
February	27,109	27,233	27,757	28,208	27,986	18,998	16,952
March	25,464	25,764	25,853	26,418	28,383	18,488	16,420
April	27,006	28,373	29,805	29,416	27,365	19,375	22,936
May	25,775	27,459	27,391	28,351	30,461	19,234	16,834
June	28,133	27,678	28,057	28,004	29,902	18,620	16,691
July	27,300	26,160	26,709	27,299	29,399	19,340	18,830
August	27,213	26,278	26,158	26,326	28,431	19,861	20,956
September	23,758	22,981	26,367	25,366	29,260	19,159	17,780
October	27,115	27,302	27,512	27,026	28,970	19,801	19,522
November	25,356	25,474	26,001	26,256	28,749	18,405	17,255
December	23,718	26,384	26,913	24,751	28,079	18,084	17,236

The coefficient was calculated as the ratio between the average AADT for Wednesdays in April and the annual AADT:

$$Coefficient = \frac{AADT \text{ on April Wednesdays}}{Annual \ AADT} = \frac{29,805}{24,448} = 1.22$$

This factor is a reduction factor that adjusts measurements taken on a Wednesday in April to the annual average conditions, smoothing seasonal peaks and ensuring that the final value is realistic for the capacity analysis.

To ensure that the analysis is representative and the model stable, the average of the two peak-hour periods was used. Following this seasonal adjustment process, the annual AADT for the road section is 5072 vehicles/day (Table A4).

Table A4. Annual AADT estimates by direction after applying the seasonal and weekly adjustment factor to the observed peak-hour traffic counts.

Direction	AADT (veh/day)
Eastbound	1726
Westbound	3346
Both directions	5072

Appendix B. Identification of Notable Crashes from Press Sources (2000–2024)

Appendix B.1. Purpose and Scope

This appendix describes the procedure used to identify and document publicly reported road traffic crashes of high severity or public relevance within the influence area of Interchange 50 (A-66, Mieres) over the period 2000–2024. The resulting records were used solely to support qualitative site contextualisation; they were not used for statistical modelling, rate estimation, or causal inference.

The results can be seen in Table A5.

Table A5. Press-based record of notable road traffic crashes identified within the influence area of Interchange 50 (A-66, Mieres) between 2000 and 2024. The table is used for qualitative site contextualisation and does not constitute a comprehensive official crash database.

Event ID	Incident Date (Reported)	Location (Reported)	Fatalities (Reported)		Publication Outlet	Headline (Abridged)	Publication Date (Reported)	Clipping ID(s)	Notes	
			Casualties	Injured					Accident Type	Case
1	8/10/03	Mieres	3		LNE La Voz de Asturias	- Los tres jóvenes muertos en accidente en Mieres volaron 30 metros desde un puente - Conmoción por la muerte de los tres jóvenes de Turón	10/11/03	02, 03, 04, 05, 06, 07, 08, 09	Rollover	Speeding
2	18/9/10	Mieres	1	2	LNE El Comercio	- Fallece en Mieres una lenense al caer a las vías del tren el coche en el que viajaba - Una mujer fallece al caer su coche a las vías del tren desde la autovía en Mieres	18/9/10	14, 14-1, 14-2, 15, 15-1	Rollover	Incorrect traffic maneuver
3	24/2/13	Mieres	1		LNE RTPA El Comercio	- Un hombre fallece tras caer con su coche al río Caudal - Fallece un hombre tras caer al río Caudal con su coche en Mieres	24/2/13	11, 12, 12-1, 13, 13-1	Rollover	Unknown
4	5/7/14	Mieres		2	SEPA	Accidente de tráfico en Mieres	5/7/14	10	Rollover	Speeding
5	13/6/18	Mieres		2	El Comercio	Dos heridos al salirse su coche desde la A-66 y caer a las vías del tren en Mieres	14/6/18	20, 21	Rollover	Driver distraction
6	5/12/21	Mieres		1	SEPA	Accidente de tráfico en Mieres	5/12/21	22	Rollover	Unknown
7	11/12/21	Mieres		1	El Comercio COPE	- Accidente en la zona del puente Mieres Sur - Aparatoso accidente en Mieres: se salta un stop, deja su coche colgado sobre la vía y da positivo	14/12/2021 13/12/2021	16, 18	Rollover	Drug use
8	31/7/23	Mieres		1	El Comercio	Una mujer resulta herida en un accidente en Mieres	31/7/23	17	Rollover	Incorrect traffic maneuver

Appendix B.2. Press Sources and Search Strategy

A structured search was conducted across digital newspaper archives and regional/local online media outlets. Search strings combined (i) infrastructure terms (e.g., A-66, interchange/exit to Mieres, Vega de Arriba, Turón), (ii) incident descriptors (e.g., crash, collision, run-off-road, rollover), and (iii) site-specific elements (e.g., bridge/overpass, ramp, merge/diverge). For each potentially relevant item, the available bibliographic information was recorded (outlet; publication date; headline; and, when accessible, edition/page reference or URL).

Appendix B.3. Eligibility Criteria

An event was included when (a) the reported location was consistent with the predefined influence area of the study site (mainline and immediate ramps), (b) an incident date could be identified (exact or approximate), and (c) the narrative contained sufficient information to associate the event with the study corridor/interchange (explicit mention of the A-66, the interchange/exit, or unambiguous geographic references). Items were excluded when they were clearly outside the study area, lacked minimum locational information, or repeated a previously identified event.

Appendix B.4. Screening and Consolidation

Candidate items were reviewed to confirm spatial relevance and to identify the incident date and location cues. When multiple items referred to the same crash, they were consolidated into a single event entry that retained all source references linked to that entry.

Appendix B.5. Data Extraction and Coding Rules

For each eligible event, the following attributes were extracted when explicitly reported: incident date, approximate location (road designation and locality), facility element involved (e.g., mainline, ramp, bridge/overpass), manoeuvre as described (e.g., exiting, merging), and reported consequences (fatalities/injuries as stated in the press item). Information not explicitly stated was coded as missing rather than inferred. Where reporting was ambiguous, entries were flagged using “reported as” wording to distinguish press descriptions from verified crash records.

Appendix B.6. Documentary Cross-Check

The resulting press-derived list was cross-checked against an archive of clippings held by the local fire service, used exclusively to corroborate dates and location cues and to reduce the likelihood of missed or duplicated events. This cross-check was applied as a consistency check and did not replace the structured search of digital press archives.

Appendix B.7. Limitations

Press coverage is inherently non-systematic and may introduce selection bias related to severity, public interest, and archival availability. Consequently, the resulting inventory should not be interpreted as an exhaustive crash register. It is used exclusively for qualitative triangulation and contextual description of the study site.

Appendix C. Official DGT Crash Record Extract (Original Document in Spanish)

The following appendix reproduces an official extract provided by the Dirección General de Tráfico (DGT) for the A-66 motorway in the vicinity of Junction 50 (Mieres, Asturias, Spain), covering the period 2015–2024. The extract is included verbatim in Spanish for traceability and to preserve the original wording and formatting.

References

1. World Health Organization. *Global Status Report on Road Safety 2023: Country and Territory Profiles*; WHO: Geneva, Switzerland, 2024.
2. Vision Zero Academy Vision Zero—No Fatalities or Serious Injuries Through Road Accidents. 1997. Available online: <https://www.roadsafetysweden.com/about-the-conference/vision-zero---no-fatalities-or-serious-injuries-through-road-accidents/#:~:text=In 1997%2C> (accessed on 17 March 2025).
3. Elvik, R. A Re-Parameterisation of the Power Model of the Relationship between the Speed of Traffic and the Number of Accidents and Accident Victims. *Accid. Anal. Prev.* **2013**, *50*, 854–860. [\[CrossRef\]](#)
4. Johansson, R. Vision Zero—Implementing a Policy for Traffic Safety. *Saf. Sci.* **2009**, *47*, 826–831. [\[CrossRef\]](#)
5. Mathes, J. On the Way to Vision Zero—No Car Without Driver Assistance. *ATZ Worldw.* **2023**, *125*, 32–35. [\[CrossRef\]](#)
6. Hartmann, A.; Abel, S. How Oslo Achieved Zero. *Inst. Transp. Eng. ITE J.* **2020**, *90*, 32–38.
7. Dragan, K.L.; Glied, S.A. Major Traffic Safety Reform and Road Traffic Injuries Among Low-Income New York Residents, 2009–2021. *Am. J. Public Health* **2024**, *114*, 633–641. [\[CrossRef\]](#)
8. Melchor, I.; Nolasco, A.; Moncho, J.; Quesada, J.A.; Pereyra-Zamora, P.; García-Sencherms, C.; Tamayo-Fonseca, N.; Martínez-Andreu, P.; Valero, S.; Salinas, M. Trends in Mortality Due to Motor Vehicle Traffic Accident Injuries between 1987 and 2011 in a Spanish Region (Comunitat Valenciana). *Accid. Anal. Prev.* **2015**, *77*, 21–28. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Castro-Nuño, M.; Arévalo-Quijada, M.T. Assessing Urban Road Safety through Multidimensional Indexes: Application of Multicriteria Decision Making Analysis to Rank the Spanish Provinces. *Transp. Policy* **2018**, *68*, 118–129. [\[CrossRef\]](#)
10. Observatorio Del Transporte y La Logística En España. *Informe Anual 2024*; Ineco: Madrid, Spain, 2025.
11. Navarro-Moreno, J.; de Oña, J.; Calvo-Poyo, F. How Do Road Infrastructure Investments Affect Powered Two-Wheelers Crash Risk? *Transp. Policy* **2023**, *138*, 60–73. [\[CrossRef\]](#)
12. Prakash Giri, O.; Bahadur Shahi, P.; Selvam, J.; Poddar, S.; Bhaumik, A. Road Traffic Regulation and Enforcement Status: A Nepalese Traffic Police Perspective. *Transp. Res. Interdiscip. Perspect.* **2024**, *26*, 101188. [\[CrossRef\]](#)
13. DGT 1.806 Personas Fallecieron En 2023 En Siniestros de Tráfico. 2024. Available online: <https://www.dgt.es/comunicacion/notas-de-prensa/20241014-1.806-personas-fallecieron-en-2023-en-siniestros-de-traffic/#:~:text=Respecto> (accessed on 12 October 2024).
14. Martínez-Gabaldón, E.; Martínez-Peréz, J.; Méndez, I. An Empirical Characterization of High-Risk Drivers in Spain. The Role of Gender, Age, Marital Status and Education. *Transp. Res. Part F Traffic Psychol. Behav.* **2019**, *66*, 430–444. [\[CrossRef\]](#)
15. Casado-Sanz, N.; Guirao, B.; Attard, M. Analysis of the Risk Factors Affecting the Severity of Traffic Accidents on Spanish Crosstown Roads: The Driver’s Perspective. *Sustainability* **2020**, *12*, 2237. [\[CrossRef\]](#)
16. Febres, J.D.; Mariscal, M.Á.; Herrera, S.; García-Herrero, S. Pedestrians’ Injury Severity in Traffic Accidents in Spain: A Pedestrian Actions Approach. *Sustainability* **2021**, *13*, 6439. [\[CrossRef\]](#)
17. Mimi, M.S.; Chakraborty, R.; Barua, S.; Das, S.; Khan, M.N.; Dadashova, B. Demographic Risk Factors and Injury Severity Scores in Substance-Use Behaviour Related Traffic Crashes. *Transp. Res. Part F Traffic Psychol. Behav.* **2025**, *108*, 168–187. [\[CrossRef\]](#)
18. Butilă, E.V.; Boboc, R.G. Urban Traffic Monitoring and Analysis Using Unmanned Aerial Vehicles (UAVs): A Systematic Literature Review. *Remote Sens.* **2022**, *14*, 620. [\[CrossRef\]](#)
19. Kaufmann, S.; Kerner, B.S.; Rehborn, H.; Koller, M.; Klenov, S.L. Aerial Observations of Moving Synchronized Flow Patterns in Over-Saturated City Traffic. *Transp. Res. Part C Emerg. Technol.* **2018**, *86*, 393–406. [\[CrossRef\]](#)
20. Khan, M.A.; Ectors, W.; Bellemans, T.; Janssens, D.; Wets, G. Unmanned Aerial Vehicle–Based Traffic Analysis: Methodological Framework for Automated Multivehicle Trajectory Extraction. *Transp. Res. Rec. J. Transp. Res. Board* **2017**, *2626*, 25–33. [\[CrossRef\]](#)
21. Luo, H.; Chu, S.-C.; Wu, X.; Wang, Z.; Xu, F. Traffic Collisions Early Warning Aided by Small Unmanned Aerial Vehicle Companion. *Telecommun. Syst.* **2020**, *75*, 169–180. [\[CrossRef\]](#)
22. Outay, F.; Mengash, H.A.; Adnan, M. Applications of Unmanned Aerial Vehicle (UAV) in Road Safety, Traffic and Highway Infrastructure Management: Recent Advances and Challenges. *Transp. Res. Part A Policy Pract.* **2020**, *141*, 116–129. [\[CrossRef\]](#)
23. Reichardt, D. A Real-Time Approach to Traffic Situation Representation from Image Processing Data. In *Proceedings of the Proceedings of the Intelligent Vehicles ’95. Symposium*; IEEE: New York, NY, USA, 1995; pp. 500–505.
24. Obaid, L.; Hamad, K.; Al-Ruzouq, R.; Abu Dabous, S.; Ismail, K.; Alotaibi, E. State-of-the-Art Review of Unmanned Aerial Vehicles (UAVs) and Artificial Intelligence (AI) for Traffic and Safety Analyses: Recent Progress, Applications, Challenges, and Opportunities. *Transp. Res. Interdiscip. Perspect.* **2025**, *33*, 101591. [\[CrossRef\]](#)
25. Khan, M.A.; Ectors, W.; Bellemans, T.; Janssens, D.; Wets, G. Unmanned Aerial Vehicle-Based Traffic Analysis: A Case Study for Shockwave Identification and Flow Parameters Estimation at Signalized Intersections. *Remote Sens.* **2018**, *10*, 458. [\[CrossRef\]](#)
26. Berghaus, M.; Lamberty, S.; Ehlers, J.; Kalló, E.; Oeser, M. Vehicle Trajectory Dataset from Drone Videos Including Off-Ramp and Congested Traffic—Analysis of Data Quality, Traffic Flow, and Accident Risk. *Commun. Transp. Res.* **2024**, *4*, 100133. [\[CrossRef\]](#)
27. Zhao, J.; Ma, R.; Wang, M. High-Precision Vehicle Trajectory Data from an Intersection in Shanghai: A Unique Dataset for Microscopic Traffic Flow Studies Collected by Drone and GNSS Receiver. *Data Brief* **2024**, *57*, 110864. [\[CrossRef\]](#) [\[PubMed\]](#)

28. Tang, F.; Liu, Z.; Wang, Z.; Li, N. Analysis of Traffic Conflict Characteristics and Key Factors Influencing Severity in Expressway Interchange Diverging Areas: Insights from a Chinese Freeway Safety Study. *Sustainability* **2025**, *17*, 8419. [\[CrossRef\]](#)
29. Xie, K.; Ozbay, K.; Yang, H.; Li, C. Mining Automatically Extracted Vehicle Trajectory Data for Proactive Safety Analytics. *Transp. Res. Part C Emerg. Technol.* **2019**, *106*, 61–72. [\[CrossRef\]](#)
30. Yang, D.; Ozbay, K.; Xie, K.; Yang, H.; Zuo, F.; Sha, D. Proactive Safety Monitoring: A Functional Approach to Detect Safety-Related Anomalies Using Unmanned Aerial Vehicle Video Data. *Transp. Res. Part C Emerg. Technol.* **2021**, *127*, 103130. [\[CrossRef\]](#)
31. Shawky, M.; Alsobky, A.; Al Sobky, A.; Hassan, A. Traffic Safety Assessment for Roundabout Intersections Using Drone Photography and Conflict Technique. *Ain Shams Eng. J.* **2023**, *14*, 102115. [\[CrossRef\]](#)
32. Espadaler-Clapés, J.; Fonod, R.; Barmounakis, E.; Geroliminis, N. An Accurate Safety and Congestion Monitoring Framework with a Swarm of Drones. *Transp. Res. Interdiscip. Perspect.* **2025**, *32*, 101490. [\[CrossRef\]](#)
33. Bhavsar, Y.M.; Zaveri, M.S.; Raval, M.S.; Zaveri, S.B. Evaluating Defensive Driving Behaviour Based on Safe Distance between Vehicles: A Case Study Using Computer Vision on UAV Videos at Urban Roundabout. *Multimodal Transp.* **2025**, *4*, 100227. [\[CrossRef\]](#)
34. Feudjio, S.L.T.; Jackai, I.N., II; Ngwah, E.C.; Fondzenyuy, S.K.; Ndingwan, T.L.; Usami, D.S.; Persia, L. Exploring the Contribution of Road Infrastructure and Environmental Factors to Crash Severity at Intersections in Mixed Traffic Settings. *Infrastructures* **2025**, *10*, 317. [\[CrossRef\]](#)
35. Mavromatis, S.; Matragos, V.; Markos, K.; Kontizas, A. Rural Roads' Passing Sight Distance Control Along Crest Vertical Curves. *Infrastructures* **2025**, *10*, 215. [\[CrossRef\]](#)
36. Ministerio de Fomento. *Guía de Nudos Viarios*; Ministerio de Fomento: Madrid, Spain, 2012.

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