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RESEARCH

A Multi-source taxonomy of urban events affecting mobility: framework development and EU-wide pilot application

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Abstract
Cascading urban disruptions, from routine roadworks to regional floods, affect mobility in ways that cut across employment, health services, and economic productivity. Yet no standardised methodology exists to synthesise heterogeneous disruption data across scales for sustainable city planning. This paper develops and applies a replicable faceted classification scheme (hereafter "taxonomy") and a multi-source integration workflow for urban events affecting mobility. The methodology rests on three pillars: a systematic literature review (123 papers), a pan-European citizen survey (n = 140), and analysis of official disaster databases (the Emergency Events Database [EM-DAT], 4,179 events; the Copernicus Emergency Management Service [CEMS], 962 activations). Standardised crosswalk tables and thematic comparison across sources enable consistent aggregation across these sources under the common taxonomy. Pilot patterns from the application indicate that transport-related disruptions are consistently salient across sources: 85.0% of survey respondents report roadworks and 62.9% public-transport delays. Temporal clustering is pronounced, with 38.5% of reported events occurring within the previous week. Inter-coder reliability for the crosswalk coding reached $\kappa \geq 0.75$. Preparedness baselines suggest limited readiness: only 19.9% of respondents report being well or fully prepared. The taxonomy, crosswalk tables, and integration workflow provide a methodological foundation and pilot-stage design guidelines for urban disruption monitoring; full field validation will require sustained longitudinal data collection, probability-based sampling, and independent replication.

Keywords Urban mobility disruptions · Multi-source data integration · Event taxonomy · Disaster risk reduction · Sustainable urban transport

Abbreviations

CEMS	Copernicus emergency management service
DRR	Disaster risk reduction
EM-DAT	Emergency events database
ESS	Effective sample size
GDPR	General data protection regulation
GEOSS	Global earth observation system of systems
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
PT	Public transport

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RQ	Research question
SLR	Systematic literature review
UNDRR	United nations office for disaster risk reduction

1 Introduction

Urban mobility underpins the daily functioning of cities and their long-term sustainability (Serdar et al. 2022). When disruptions strike, whether a burst water main that blocks a bus corridor or a heatwave that buckles rail tracks, the consequences ripple through employment, health services, social inclusion, and economic productivity (Xu and Chopra 2023; Brunner et al. 2024). International policy, including the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations Office for Disaster Risk Reduction (UNDRR) 2015) and the EU Climate Adaptation Strategy (European Commission 2021), calls for prevention, preparedness, and multi-hazard risk understanding. Yet most existing frameworks remain anchored in single data sources or single spatial scales, and no cross-domain classification scheme provides an explicit mechanism for harmonising citizen-reported, database-recorded, satellite-observed, and literature-derived disruption categories within a single analytical structure (Hickford et al 2018; Zhou et al. 2024).

The same disruption event may appear quite differently depending on the evidence stream that records it. A flood that triggers a Copernicus Emergency Management Service activation may also surface in citizen survey responses as "impassable roads," in disaster databases as an entry meeting mortality or economic-loss thresholds, and in the academic literature as a case study of cascading infrastructure failure (Brunner et al. 2024; Zafeiropoulos et al. 2023). Without a standardised classification that bridges these perspectives, cross-source synthesis remains ad hoc (Carramiñana et al. 2024). A unified taxonomy is therefore needed to enable consistent comparison and to support evidence-based planning for sustainable urban transport (Yabe et al. 2022).

The paper's primary contribution is the development of a classification methodology comprising a faceted scheme (hereafter "taxonomy"), standardised crosswalk tables, and a transparent integration workflow. The paper does not present a validated implementation system; rather, it demonstrates that these tools can be applied consistently across heterogeneous European data sources, and it derives from this application a set of illustrative pilot patterns and preliminary design guidelines. The paper should accordingly be evaluated on the replicability and transferability of its methods, and on the clarity with which it distinguishes what the pilot demonstrates from what must await future longitudinal data (Barbero et al. 2023).

Following this introduction, Sect. 2 reviews the literature on classification and ontology design, cascading failures in urban mobility, multi-source data fusion, citizen sensing, and the European disaster risk reduction policy context. Section 3 describes the methodology, including the guiding proposition, the research questions, and the three evidence-gathering instruments used in this study. A dedicated subsection (Sect. 3.2) sets out the design rationale for the proposed taxonomy and clarifies its terminological status. Section 4 presents the findings, organised by level of evidence, and Sect. 5 discusses them in relation to the guiding proposition and the wider literature. Finally, Sect. 6 provides concluding remarks, contributions, limitations, and directions for future research.

2 Background and related work

This section reviews five interrelated bodies of work that together frame the present study: classification and ontology design for urban events; cascading failures and transport disruption analytics; multi-source data fusion for disaster event mapping; citizen sensing and the European disaster risk reduction policy context; and a synthesis of the main research gaps. The ordering is deliberate: classification theory is placed first because it provides the conceptual foundation against which domain-specific studies are subsequently assessed.

2.1 Classification and ontology design for urban events

Classification is the conceptual prerequisite for cross-source synthesis. Shiyali Ramamrita Ranganathan (1967) articulated the theoretical basis of faceted classification, arguing that multi-dimensional phenomena are better represented by a small number of orthogonal facets than by rigid hierarchical categories. Prieto-Díaz (1991), extending Ranganathan's principles to applied information systems, showed that faceted schemes support reuse and extensibility precisely because they decouple independent descriptive dimensions. In the ontology-engineering tradition, Gruber (1993) defined an ontology as a formal, explicit specification of a shared conceptualisation, and set out design criteria, clarity, coherence, extendibility, minimal ontological commitment, that remain foundational for controlled vocabularies. Smith and Ceusters (2010), working within the realist tradition, proposed a methodology for the coordinated evolution of scientific ontologies in which categories are grounded in real-world entities and their relations rather than in convenience of classification alone.

Despite this theoretical maturity, applied urban event schemes remain largely domain-specific. Hickford et al (2018) and Zhou et al. (2024) have documented the proliferation of discipline-specific classifications in transport resilience and urban infrastructure research, with transport-oriented schemes rarely interoperable with hazard-oriented ones, and vice versa. Emergency-management taxonomies, including those embedded in EM-DAT (Delforge et al. 2025) and the Copernicus EMS activation catalogue (European Commission Joint Research Centre 2012), structure the large-scale end of the disruption spectrum, but do not address daily or mid-scale events that dominate citizen experience. None of these schemes provide an explicit crosswalk mechanism for harmonising citizen-reported, database-recorded, satellite-observed, and literature-derived categories within a single structure. The gap addressed by the present study is therefore specific: no classification scheme currently bridges these four source types under a single analytical taxonomy with published crosswalk rules.

The implications for sustainable city governance are direct. Without interoperable classification, municipal authorities cannot aggregate evidence across the sources they routinely receive, and cross-jurisdictional comparison remains artisanal rather than systematic.

2.2 Cascading failures and transport disruption analytics

Cascade dynamics are central to disruption impact modelling in interdependent urban systems. Boeing and Ha (2024) simulated street-network disruptions across every urban area in the world and demonstrated that connectivity and redundancy dampen cascading effects when high-centrality nodes fail. Brunner et al. (2024) modelled cascading risks through real-world interdependent urban infrastructure and showed that failures can amplify or attenuate depending on network topology, which reinforces the need for multi-domain perspectives. Hickford et al (2018), reviewing resilience engineering across interdependent infrastructure sectors, argued that cross-sector planning is essential because failures in one domain routinely propagate into others. Thaler et al. (2025), through a distributed co-simulation of flood-triggered cascades across water, electricity, gas, and telecommunications networks, documented the same cross-sector pattern in a digital-twin setting. Serdar et al. (2022) reviewed indicators, disturbance typologies, and assessment methods for urban transportation networks, while Xu and Chopra (2023) showed that interconnectedness across modes enhances network resilience in safe-to-fail mobility systems.

Yabe et al. (2022); Yabe (2021); Yabe et al. (2020) have developed data-driven approaches using large-scale mobility data and Bayesian modelling, documenting how socio-physical interdependencies produce uneven recovery trajectories. Yadav et al. (2020) applied percolation theory to compound flood-attack scenarios, revealing that efficiency-oriented design can heighten vulnerability. Poudel et al. (2022) used the SYNER-G framework to quantify interdependencies among water, power, and health systems, and reported amplification effects alongside integrated mitigation opportunities. Rajput and Mostafavi (2023), using motif analysis on temporal mobility networks, showed that sub-structural impacts persist well beyond apparent global recovery, which challenges simplistic restoration assumptions.

It may be observed that these studies model cascades and quantify impact with considerable sophistication, yet classification remains post hoc: events are categorised after the modelling exercise, not before, and no common prospective coding framework is offered for multi-source intake. The implication for sustainable mobility policy is that cascade-aware planning requires a classification structure that can be applied to incoming evidence before analysis, not only retrospectively.

2.3 Multi-source data fusion for disaster event mapping

Integrating heterogeneous data is a methodological frontier in disaster mapping. Carramiñana et al. (2024) combined agent-based, network-based, and system-oriented simulators with layered indicators for explainable risk assessment. Zafeiropoulos et al. (2023) presented a framework that couples Earth Observation data from the Global Earth Observation System of Systems (GEOSS) and Copernicus with crowdsourced information and in-situ measurements, with explicit General Data Protection Regulation compliance, and provides a direct benchmark for the present Copernicus EMS integration. Zhou et al. (2024) analysed 958 documents on urban resilient infrastructure bibliometrically and reported growing uptake of artificial intelligence in data-fusion workflows. Tariverdi et al. (2023) implemented multi-source fusion for infrastructure criticality assessment in Lima and Manila by combining OpenStreetMap, WorldPop, GPS traces, and flood modelling. Barbero et al. (2023) adopted an EU-wide mixed-methods consultation with triangulation across multiple evidence streams to investigate the training–energy-efficiency relationship in construction, and their methodological approach directly parallels the multi-source strategy used in the present study. Deng (2021) provides contextual observations on large-scale locational-data analytics for urban resilience.

Table 1 summarises, for each of these contributions, the sources integrated and the harmonisation mechanism employed. It is of particular interest that, although several

Table 1 Sources integrated and harmonisation mechanisms in representative multi-source disaster and resilience studies. The rightmost column records whether an explicit, reusable crosswalk between source-specific categories and a common taxonomy is provided

Study	Sources integrated	Harmonisation mechanism	Explicit crosswalk
Carramiñana et al. (2024)	Agent-based, network-based, and system-oriented simulators; layered indicators	Layered indicator aggregation	No
Zafeiropoulos et al. (2023)	GEOSS and Copernicus Earth Observation; crowdsourced reports; in-situ measurements	Platform-level integration with GDPR controls	No (platform-level)
Zhou et al. (2024)	Bibliometric corpus (958 documents) on urban resilient infrastructure	Bibliometric mapping and topic clustering	No
Tariverdi et al. (2023)	OpenStreetMap; WorldPop; GPS traces; flood modelling	Criticality-weighted spatial overlay	No
Barbero et al. (2023)	Questionnaire; interviews; use cases; expert workshop	Thematic triangulation across instruments	No (thematic only)
Brunner et al. (2024)	Interdependent infrastructure datasets; network models	Topological cascade modelling	No
Present study	Systematic literature review; citizen survey; EM-DAT; CEMS; supplementary social media	Faceted taxonomy with documented crosswalk tables and coding rules	Yes (Supp. Table S1)

studies combine multiple sources, none provides an explicit, published crosswalk table that maps heterogeneous source-specific categories onto a single multi-dimensional taxonomy with documented coding rules. The gap that the present paper addresses is therefore not the combination of sources per se, but the absence of a reusable mapping artefact that other research teams can apply, audit, and extend.

The implication for sustainable city planning is that the value of an integrated monitoring capability depends not only on the sources combined, but on the transparency of the classification rules used to combine them. Without such transparency, aggregated figures cannot be audited and cross-jurisdictional comparison is compromised.

2.4 Citizen sensing and European disaster risk reduction policy context

Citizen-generated data are increasingly regarded as a necessary complement to official sources in disaster risk reduction. Zafeiropoulos et al. (2023) demonstrated GDPR-compliant integration of crowdsourced data with Earth Observation systems for pan-European resilience planning. Kott and Linkov (2022), reflecting on lessons from the COVID-19 emergency response, emphasised multi-source decision-making under uncertainty and the importance of preparedness baselines derived from citizen-level data. Liu et al. (2023) analysed daily mobility across 313 Chinese cities to quantify combined epidemic-weather impacts on urban recovery. Whilst European social sensing benefits from mature digital infrastructure and strong privacy regulation, standardised intake pathways from citizen-generated data into official disaster risk reduction systems remain under-developed.

The Sendai Framework provides guidelines for Disaster Risk Reduction globally (United Nations Office for Disaster Risk Reduction (UNDRR) 2015). Its 2023 midterm review, however, acknowledged persistent gaps at the local level, with policies still tilted toward response rather than prevention (UNDRR 2023). Perera and Biljecki (2024) surveyed urban disaster risk reduction management since the Framework's adoption and highlighted digital twins and integrated data platforms as promising but under-explored. The European regulatory architecture, including the Union Civil Protection Mechanism (European Commission 2023b), the 2021 EU Climate Adaptation Strategy (European Commission 2021), and the 2023 EU Disaster Resilience Goals (European Commission 2023a), creates institutional demand for harmonised disruption data across jurisdictions. The applied tools required to deliver such harmonisation, however, are not yet standardised at the event-classification level, a gap that standardised taxonomies and crosswalk tables are well placed to address. The implication for urban managers is that aggregating citizen-reported mobility disruptions into policy-relevant categories requires a coding infrastructure that is presently missing.

2.5 Summary and research gaps

On the basis of the preceding synthesis, four research gaps can be identified, each tied to a specific deficiency documented in the literature reviewed above.

Gap 1: *No cross-domain faceted classification with published crosswalk mechanisms*. Existing urban-event schemes are largely domain-specific and do not provide explicit crosswalk rules for translating between heterogeneous source-specific categories (Hickford et al 2018; Zhou et al. 2024). The classification-theory literature (Shiyali Ramamrita Ranganathan 1967; Prieto-Díaz 1991; Gruber 1993; Smith and Ceusters 2010) offers the conceptual tools, but these have not been applied systematically to multi-source urban disruption data.

Gap 2: *No multi-source harmonisation framework bridging citizen, database, satellite, and literature sources*. The multi-source fusion studies reviewed in Table 1 integrate subsets of sources but none publishes a reusable crosswalk artefact that spans all four source types under a common taxonomy (Carramiñana et al. 2024; Zafeiropoulos et al. 2023; Tariverdi et al. 2023; Barbero et al. 2023).

Gap 3: *Blurred distinction between baseline exploration and validated monitoring*. Existing studies frequently present exploratory findings and applied monitoring implications together, without clearly separating baseline evidence, illustrative patterns, and fully validated implemented systems (Rözer et al. 2022).

Gap 4: *Absence of empirically grounded, even if provisional, design guidelines*. Although many frameworks invoke Sendai principles (United Nations Office for Disaster Risk Reduction (UNDRR) 2015), few translate them into concrete design starting points, such as update frequency, spatial resolution, and historical depth, that are grounded in pilot evidence and explicitly flagged as provisional.

This study addresses these gaps by: (i) developing a domain-by-scale faceted taxonomy with published coding rules and crosswalk tables; (ii) applying the taxonomy consistently across five heterogeneous source types; (iii) clarifying, without claiming to resolve through validation, the distinction between exploratory baseline research and validated monitoring: the paper labels explicitly what the pilot demonstrates, what is illustrative, and what must await longitudinal validation, and it sets out a concrete validation pathway (Sect. 5.4) rather than delivering a validated monitoring system; and (iv) deriving preliminary design guidelines from the pilot evidence, explicitly labelled as such.

3 Methodology

This section outlines the methodological design of the study. It first states the guiding proposition and research questions; it then sets out the design rationale for the proposed taxonomy; and it finally describes the evidence-gathering instruments, integration workflow, and analytical procedures used to develop and evaluate the taxonomy across multiple data sources.

3.1 Guiding proposition and research questions

The study is framed around the following guiding proposition, stated as a matter of applicability, consistency, and feasibility rather than of comparative performance: *an evidence-based urban mobility disruption taxonomy can be applied consistently and feasibly to contextualise and analyse multi-source incident data under pilot baseline conditions, yielding coherent domain-level patterns across heterogeneous sources.* No baseline or alternative classification approach is evaluated against the taxonomy in this paper; no claim of comparative enhancement is therefore made or tested, and the pilot evidence speaks to whether the taxonomy is applicable, consistent, and feasible, not to whether it outperforms alternatives.

Three questions guide the study, each addressing a different aspect of this proposition:

- RQ1: How can heterogeneous urban disruption data sources be harmonised through a unified taxonomy while preserving source-specific detail?
- RQ2: What disruption patterns emerge across European cities when multiple evidence streams are analysed together, and to what extent are these patterns consistent across sources?
- RQ3: What preliminary design guidelines, concerning update frequency, spatial resolution, and thematic priority, can be derived from pilot evidence to inform future implemented monitoring?

3.2 Taxonomy design rationale

Before the methods themselves are described, it is necessary to clarify what kind of artefact is being proposed and why its structure was chosen. This subsection therefore addresses three matters: terminology; the rationale for the domain-by-scale structure; and the alternative structures that were considered and rejected.

Terminological clarification The artefact proposed in this paper is best described as a *faceted classification scheme* in the sense of Shiyali Ramamrita Ranganathan (1967) and Prieto-Díaz (1991), accompanied by a set of crosswalk tables that function as a coding framework for applied research. The term *taxonomy* is adopted throughout for readability and consistency with the wider urban-resilience literature, but no claim is made of full ontological commitment in the sense of Gruber (1993) or Smith and Ceusters (2010): the scheme does not axiomatise relations between categories, nor does it specify formal inheritance rules or machine-readable semantics. A future extension of this work might promote the scheme to a full ontology; for present purposes, a faceted taxonomy with explicit crosswalks is the appropriate artefact because it is sufficient for reproducible multi-source coding without committing prematurely to formal semantics that the underlying data do not yet support.

Rationale for the domain-by-scale structure Three considerations motivate the two-facet structure adopted in this paper. First, it may be observed that, across the reviewed literature, urban-event studies tend to classify along one of two dimensions: the kind of event, typically understood through a sector or hazard category, and the spatial or functional reach of the event, usually approximated through ordinal scale bands. Separating these into orthogonal facets, in line with Ranganathan's principle of faceted design, enables consistent coding of the many events that are mixed in kind and scale, for example a localised utility outage triggered by a regional storm. Second, the facets align with the categorical structures used by the principal evidence streams integrated in this study: the Copernicus EMS activation catalogue and EM-DAT both use disaster-type categories that map naturally onto the domain facet (Delforge et al. 2025; European Commission Joint Research Centre 2012), whilst citizen surveys and literature reports more readily distinguish events by functional reach. Third, the structure supports the methodological requirement that coding be transparent to non-specialists: city officials, researchers, and citizens can recognise and apply the two facets without requiring domain expertise in ontology engineering.

Alternative structures considered Three alternative structures were considered and set aside, each for specific reasons. A *single-hierarchy disaster-type taxonomy*, modelled on the EM-DAT disaster group structure (Delforge et al. 2025), was rejected because it collapses daily and mid-scale service disruptions (roadworks, signal outages) that dominate citizen experience into an undifferentiated "other" category. A *phase-based taxonomy* organised around the Sendai preparedness, response, and recovery phases (United Nations Office for Disaster Risk Reduction (UNDRR) 2015) was rejected because event-level coding across heterogeneous sources, particularly retrospective survey responses, does not reliably carry phase information. A *cascade-graph representation*, in the tradition of Brunner et al. (2024) and Boeing and Ha (2024), was considered and set aside as premature: whilst cascade relations are central to impact modelling, they require event-level temporal alignment that the present study cannot yet provide, and their introduction before the baseline classification is stabilised would conflate two distinct modelling steps. The domain-by-scale faceted structure is therefore the minimum scheme that supports consistent cross-source coding without over-committing to structures the pilot data cannot yet support.

3.3 Evidence-gathering instruments

The study rests on three core evidence-gathering instruments, supplemented by a social media dataset used for corroboration only. Figure 2 presents the integration workflow. The pilot study spans a pan-European sample with four focal cities. Data collection took place during 2025 and is intended to provide baseline evidence for the taxonomy's applicability rather than population-level estimates of disruption prevalence. Limitations arising from the current stage of data maturity are documented rather than glossed over, since they define the requirements for subsequent longitudinal evaluation.

3.3.1 Systematic literature review (SLR)

A peer-reviewed corpus (2015–2025) on urban mobility disruptions was assembled. Screening followed PRISMA 2020 guidelines (Page et al. 2021) (Fig. 1). Database searching identified 2,394 records; removal of 514 duplicates yielded 1,880 unique records for title and abstract screening.

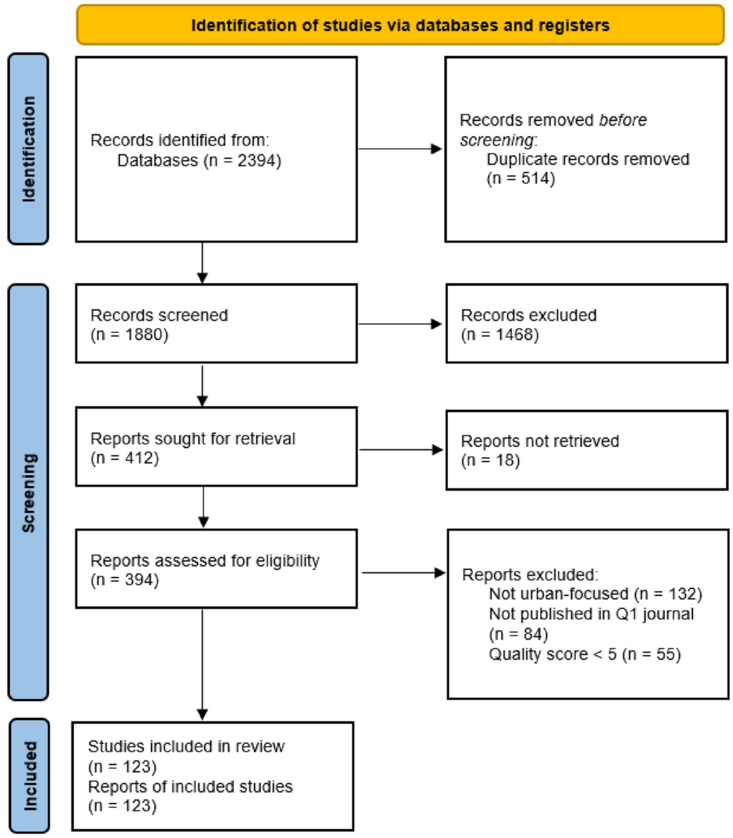
Title and abstract screening excluded 1,468 records against four predefined eligibility criteria: (i) publication in a peer-reviewed journal between 2015 and 2025; (ii) explicit focus on urban or metropolitan mobility, transport disruption, or mobility-relevant infrastructure; (iii) an empirical, methodological, or review contribution relevant to event classification, disruption impacts, or multi-source data integration; and (iv) publication in a journal ranked in the first quartile (Q1) of its Scopus subject category. Two reviewers screened all records independently; disagreements were resolved through discussion, and records that remained uncertain at the title and abstract stage were retained for full-text assessment rather than excluded. The principal reasons for exclusion at this stage were: absence of an urban mobility or disruption dimension; non-urban settings, such as intercity, maritime, or aviation contexts without an urban interface; purely technical contributions without an event or disruption perspective; editorial and commentary pieces; and publication outside Q1-ranked journals. Full-text assessment of the remaining 412 records led to a final corpus of 123 included papers. Qualitative synthesis used grounded theory (open, axial, and selective coding) in NVivo to identify disruption-to-impact pathways and conceptual categories.

The Q1 restriction was adopted as a pragmatic quality-assurance criterion: it provides an auditable, externally defined proxy for methodological rigour and kept the corpus within the capacity of dual independent coding. It is, however, acknowledged as a possible source of publication and disciplinary bias, since it excludes emerging journals, practitioner and grey literature, and regional outlets in which European disruption evidence may also appear; this limitation is revisited in Sect. 5.

3.3.2 Pan-European citizen survey

The survey serves as an illustrative application of the taxonomy to citizen-reported data. Given the effective sample size after post-stratification weighting (ESS $\approx$ 36), survey-derived patterns are treated throughout this paper as indicative rather than as population-level estimates. A multilingual online questionnaire ($n = 140$ responses across a pan-European sample) captured self-reported disruption experiences, coping strategies, and perceived city resilience. The full survey instrument is provided in Supplementary Material S2.

Fig. 1 PRISMA 2020 flow diagram for the systematic literature review study selection process



Post-stratification weighting was necessary to address geographic imbalance (Greek over-representation: 56.4% of the raw sample versus a 3.5% population target), but it increased variance substantially. Following Kish (Kish 1965), the design effect is:

$$\mathrm{Deff} = 1 + \mathrm{CV}(w)^2 = 1 + \frac{\mathrm{Var}(w)}{\bar{w}^2} \tag{1}$$

where w denotes individual survey weights. The effective sample size is then:

$$\mathrm{ESS} = \frac{n}{\mathrm{Deff}} = \frac{(\sum w_i)^2}{\sum w_i^2} \approx 36 \tag{2}$$

Post-stratification targeted adult (18+) populations from Eurostat 2026 estimates across the sampled countries. Weights were trimmed at $4\times$ the mean following Kish (Kish 1992) to balance variance reduction against bias. Only geographic weighting was applied; small cell sizes precluded demographic calibration by age or gender.

With ESS $\approx$ 36 and a non-probability sample, formal confidence intervals are not reported, since they would convey unwarranted precision. To signal the order of magnitude of sampling imprecision, an indicative range of approximately ±12 to 17 percentage points across the observed proportion range (about ±17 near 50%, narrower at extreme proportions), computed as $\pm 2\sqrt{p(1-p)/\mathrm{ESS}}$, is noted alongside key tables; these values are approximate design-based indications intended solely to discourage over-interpretation of point estimates, and they are not formal confidence intervals. Survey-derived percentages should be read as illustrative indicators of the framework's applicability, not as population estimates for European cities. Comparable pilot-stage multi-source studies have been published with similar or smaller questionnaire samples when the primary contribution is methodological rather than epidemiological; for example, Barbero et al. (2023) reported EU-wide consultation findings from $n = 52$ questionnaire respondents in this journal, with the sample size acknowledged as a limitation rather than treated as disqualifying.

3.3.3 Database analysis: EM-DAT and Copernicus EMS

International disaster records meeting specific mortality or economic-loss thresholds (2000 to July 2025) were obtained from the EM-DAT database (Delforge et al. 2025). Satellite-derived activation records from the Copernicus Emergency Management Service for preparedness, rapid mapping, and recovery support (2012 to July 2025) (European Commission Joint Research Centre 2012; European Commission 2012) provide authoritative spatial footprints for large-scale events but offer limited temporal granularity for daily or mid-scale disruptions.

EM-DAT and CEMS were selected as the two official event databases for three reasons. First, both are publicly accessible with documented inclusion criteria, which supports the auditability requirement of the crosswalk methodology; commercial catastrophe catalogues do not permit equivalent scrutiny, and national civil-protection registers are heterogeneous in structure and coverage across Member States. Second, the two sources are complementary in what they contribute: EM-DAT supplies a long, thematically structured record of disasters meeting humanitarian-impact thresholds, whilst CEMS supplies institutionally anchored, satellite-derived spatial footprints tied to activation decisions, a combination that other candidate sources (for example DesInventar, with uneven European coverage, or alert-oriented systems such as GDACS, which are not archival) do not match. Third, both are embedded in the European disaster risk reduction data infrastructure and are therefore the sources against which a European crosswalk artefact is most likely to be reused.

Two filters were applied to both databases. Thematically, records were restricted to urban-relevant hazard types with potential mobility impacts (excluding, for example, purely agricultural drought entries). Geographically, records used in the European seasonal analysis (Sect. 4.3) were restricted to records assigned to the Europe region in EM-DAT's regional classification and, for CEMS, to activations located in European countries, whilst Fig. 4 retains the global series as context for the large-scale end of the disruption spectrum. EM-DAT spatial resolution is country-level; subnational localisation relies on supplementary sources where available.

3.3.4 Social media analytics (supplementary corroboration)

Social media data were collected from a single platform, Twitter/X, through its application programming interface between May and August 2025, subject to API constraints of approximately 300 requests per 15-min window and a typical delay of 5 to 10 min between ingestion and classification. Collection used multilingual keyword queries aligned with the taxonomy's disruption categories. After preprocessing and deduplication, including removal of exact duplicates and reposts, the corpus comprises 13,388 posts across 23 countries in 10 languages. Geographic assignment combined post metadata with geolinguistic tagging: posts were mapped to countries and to the five pilot Areas of Interest defined in the companion study, which comprise the four focal cities of the present pilot together with one additional city located in the same country as one of them, with language identification supporting country-level assignment where explicit location information was absent. For anonymisation, only a generic unique identifier, timestamp, and post text were retained; no personally identifiable information was stored. An 11-category supervised classifier, trained on an expert-annotated corpus, achieved accuracy ≈ 0.83 (Cohen's $\kappa \approx 0.79$) on a stratified held-out validation set; classifier design, annotation procedure, and per-category performance are reported in full in the companion paper. These data are used in this paper as a supplementary corroboration source only, to check whether thematic patterns from the survey are echoed in online discourse. The data reflect the usage patterns of a single platform over a narrow window, and their representativeness for broader public discourse remains open.

3.4 Cross-source comparison strategy

A key limitation is that the evidence streams do not overlap in time for the same events: the social media window (May to August 2025) does not coincide with mobility-relevant EM-DAT entries for the focal sites, and survey responses cover variable retrospective periods (past week to six months). Event-level cross-validation is therefore not attempted in this paper.

Two modes of comparison are accordingly distinguished. The first, referred to throughout as *thematic cross-source comparison* and feasible within the present study, consists of comparing domain-level patterns across sources. This mode tests whether surveys, literature, and official databases converge on the same dominant disruption domains, and it supports conceptual coherence without requiring temporal alignment. The second mode, *temporal triangulation*, would match specific events across sources in time and space so that quantitative accuracy metrics could be computed; this mode is reserved for future work and requires a sustained data-collection period during which all streams collect data concurrently. The term *triangulation* is retained in the present paper only in the narrower sense of thematic cross-source comparison, and event-level validation is not claimed.

3.5 Taxonomy and crosswalk tables

3.5.1 Two-facet taxonomy

Urban mobility disruptions are classified along two facets:

- Domain: Transport; Environment and Weather; Utilities and Connectivity; Public Space and Social.

Table 2 Two-facet event taxonomy (domain by scale) with five-level impact modifiers. The structure enables consistent coding across all data sources and serves as the foundation for crosswalk-table mapping

Event Category	Definition	Examples	Affects passenger mobility	Affects freight mobility	Affects infrastructure	Scale (per event instance)
Transport-related	Any interruption or degradation of passenger or freight movement due to infrastructure, operations, or regulation.	Congestion, Public Transport (PT) delays, roadworks, strikes	✓	✓	✓	Daily / Mid-scale / Large-scale
Environment and weather	Natural phenomena altering mobility conditions or infrastructure integrity.	Heatwaves, floods, snow or ice, storms	✓	✓	✓	Daily / Mid-scale / Large-scale
Utilities and connectivity	Failures in essential services that indirectly or directly constrain mobility.	Power or water outage, ICT breakdown	✓	✓		Daily / Mid-scale / Large-scale
Public Space and Social Events	Planned or unplanned socio-spatial activities affecting flows.	Protests, festivals, sports events, security incidents	✓	✓		Daily / Mid-scale / Large-scale

Table 3 Severity and urgency equivalence across data streams. The five-level scheme links survey impact ratings, social-media urgency labels, and Copernicus or EM-DAT disaster categories to a common scale

Level	Common label	Social-media alias	Illustrative mobility impact
5	Critical/Immediate	Critical	Full corridor closure; multi-modal cascade failure
4	High/Priority	High	Major route closure; PT rerouting >30 min
3	Moderate/Standard	Moderate	Localised delay 15–30 min; single-mode impact
2	Low/Background	Low	Minor inconvenience; no service change required
1	Very Low/Information	Very Low	Informational; no immediate mobility consequence

- Scale: Daily (routine service issues); Mid-scale (localised incidents affecting districts); Large-scale (city-wide or regional crises).

Each disruption is further qualified by a five-level impact modifier (Very Low to Critical). Table 2 presents the complete taxonomy.

Within the domain facet, categories are mutually exclusive for any single coding decision: each coded event role receives exactly one domain label. Events that cascade across domains are handled through dual-field coding: the *trigger* domain (the initiating event) and the *impact* domain (the cascaded mobility consequence) are recorded in separate fields of the harmonised record, as illustrated by the flood example in Box 1 (Table 5), where Environment is coded as the trigger and Transport as the cascaded impact. Aggregate domain counts reported in this paper are computed on the trigger (primary) domain only, so that no event contributes to more than one domain total and double-counting is avoided; impact-domain tallies can be produced separately where a cascade perspective is required. The scheme is thereby mutually exclusive within each coding field whilst remaining expressive enough to represent cross-domain cascades. The taxonomy is designed for applied clarity for diverse user groups, including city officials, researchers, citizens, and sustainability planners.

Scale distinctions reflect spatial extent, duration, and systemic consequence. Where these dimensions point in different directions, assignment follows a documented precedence rule: systemic consequence takes precedence over spatial extent, and spatial extent over duration. A short-lived metro closure that cascades into district-wide congestion is accordingly coded as Mid-scale despite its limited duration and point-like origin. Severity is assigned independently of scale using the anchored descriptions in Table 3, with the highest applicable mobility-impact description determining the level. Both rules are stated in the coding principles and illustrated in the worked examples of Supplementary Table S1.

Table 3 defines the five-level severity scheme used throughout the paper and provides a shared intensity scale across data sources.

3.5.2 Crosswalk to external classification schemes

A core methodological contribution is the crosswalk table that maps the proposed taxonomy onto existing schemes. Survey disruption categories are mapped onto taxonomy domains; EM-DAT disaster types are mapped onto taxonomy scale and domain; Copernicus EMS activation categories are mapped onto taxonomy scale and domain; social media risk classifications are mapped onto taxonomy domains as supplementary evidence; and literature disruption typologies are mapped onto taxonomy domains. The complete crosswalk, together with documented coding rules for each source, is provided in Supplementary Table S1 and is intended as a reusable artefact for other multi-source disaster risk reduction integration efforts.

Table 4 summarises the characteristics of all evidence streams and notes the complementarities and inherent limitations of each.

3.6 Qualitative analysis and reporting standards

Literature coding followed grounded theory to surface recurring themes, disruption typologies, and adaptation pathways. PRISMA 2020 compliance ensures transparency in study selection and synthesis.

3.7 Data integration workflow

Figure 2 presents the harmonisation and comparison architecture. The workflow covers: (i) taxonomy-based coding of each source; (ii) crosswalk-table application for domain mapping; (iii) spatial normalisation (population-weighted where applicable); and (iv) thematic aggregation for domain-level pattern comparison.

4 Results: illustrative application and pilot patterns

The results that follow are organised into three levels of evidence. Section 4.1 presents demonstrated findings, namely taxonomy applicability and crosswalk reliability.

Table 4 Comparative characteristics of evidence streams

Source	Temporal Coverage	Spatial Resolution	Scale Focus	Limitation
Survey	Retrospective (0–6 months)	Country	Daily–Mid	ESS≈36 after weighting
Literature (SLR)	2015–2025	Conceptual	All	Publication bias (Q1 only)
EM-DAT	2000–Jul 2025	Country-level (some sub-nat'l)	Large	Inclusion thresholds
CEMS	2012–Jul 2025	Event footprints	Large	Satellite detection only
Social Media[a]	May–Aug 2025	Inferred (geocoded)	Daily–Mid	Platform bias; API limits

ESS: effective sample size; SLR: systematic literature review;

CEMS: copernicus emergency management service

Temporal non-overlap prevents event-level validation in this pilot study

[a]Used as a supplementary corroboration source only in this paper

Section 4.2 presents illustrative patterns derived from thematic cross-source comparison. Section 4.3 presents preliminary design guidelines derived from the pilot evidence. All survey-derived percentages are drawn from a weighted baseline sample (ESS ≈ 36). Consistent with Sect. 3.3.2, no formal confidence intervals are reported; where tables note an indicative uncertainty range of roughly ±12 to 17 percentage points across the observed proportion range (about ±17 near 50%, narrower at extreme values), this is an approximate design-based indication of imprecision derived from the effective sample size, not a formal confidence interval. The percentages demonstrate that the taxonomy can be applied across diverse European contexts; they do not support population-level inference.

4.1 Harmonising heterogeneous data sources (RQ1)

This section addresses RQ1 by presenting three categories of demonstrated evidence: crosswalk reliability, the Urban Event Catalogue, and a worked example tracing a single event type across all four primary sources.

Crosswalk reliability Two independent coders applied the crosswalk tables to a stratified sub-sample of events drawn from each source. Inter-coder reliability reached $\kappa \geq 0.75$, which is consistent with a coding scheme that can be applied with acceptable consistency by different research teams. The complete crosswalk mapping is provided in Supplementary Table S1.

Urban Event Catalogue The pilot study produced a standardised Urban Event Catalogue (76 events) with harmonised metadata (domain, scale, severity, geotag, timestamp, source provenance). The catalogue supports cross-source comparison and will serve as a seed set for temporal triangulation once a sustained data-collection period enables alignment across sources.

Worked example: flood-induced road closure across four sources The centrepiece of the RQ1 evidence is a worked example that traces a single event type, a flood-induced road closure, across all four primary sources via the crosswalk (Box 1). This example demonstrates, end to end, how heterogeneous source-specific categories are mapped onto the unified taxonomy, and how the same event is represented when each source records it from its own vantage point.

Two analytical observations follow from Box 1. First, the same underlying phenomenon is recorded by each source at a different level of scale granularity: citizen reports emphasise the mid-scale mobility impact experienced locally, whilst database and satellite sources record the large-scale regional footprint. The two-axis structure accommodates this divergence without forcing a single scale assignment. Second, the cross-domain coding (Environment as trigger, Transport as impact) is explicit in the harmonised record,

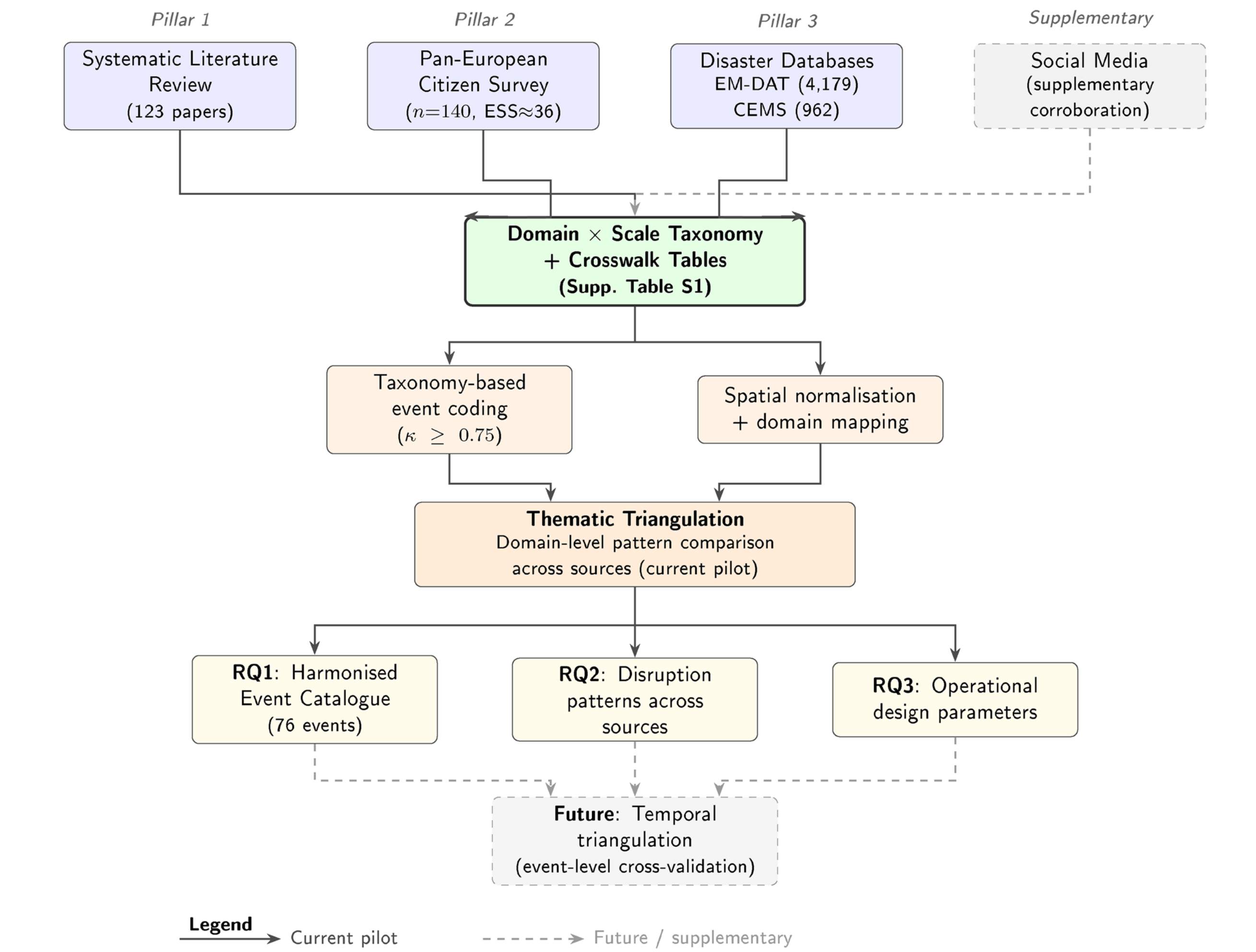


Fig. 2 Data harmonisation and comparison workflow. Present pilot study: solid arrows indicate thematic comparison and domain-level pattern comparison across sources. Future extension: dashed arrows indicate temporal triangulation (event-level cross-validation), contingent on sustained, time-aligned multi-source data

which is consistent with the cascade-aware perspective documented in the literature (Brunner et al. 2024; Hickford et al 2018). The implication for urban managers is that the taxonomy enables a single flood event to be simultaneously visible in environmental and transport dashboards without double-counting.

Cross-domain cascade pathways Beyond single-domain prevalence, the framework maps how disruptions propagate across domains. Figure 3 synthesises typical pathways from the literature and survey narratives: an initiating event, for example a power outage in the utilities domain, cascades into mobility consequences such as traffic-signal failures and irregular transit headways, and in turn affects social access and economic activity.

The pathways in Fig. 3 represent commonly co-occurring event sequences identified through literature synthesis and respondent narratives. They should be read as plausible cascade patterns, not statistically validated causal chains. Distinguishing temporal co-occurrence from verified causation requires event-level timestamped data, which the present study lacks due to temporal misalignment. The qualitative pathways serve, for now, as testable hypotheses for a future longitudinal deployment.

4.2 Illustrative disruption patterns from cross-source comparison (RQ2)

This section addresses RQ2 by presenting illustrative patterns that emerge when the three core evidence streams, supplemented by social media corroboration, are analysed together under the common taxonomy. In line with the editorial guidance accepted at revision, these findings are presented as indicative of the taxonomy's ability to differentiate between disruption types rather than as substantive conclusions about European disruption prevalence. Detailed survey breakdowns by settlement type and by resilience

Table 5 Box 1. Worked example: a flood-induced road closure traced across the four primary sources via the taxonomy crosswalk (Supplementary Table S1). Each row shows the source-native category, the mapped domain and scale under the proposed taxonomy, and the resulting harmonised record. The example illustrates how temporally misaligned sources still yield coherent domain-level coding

Source	Source-native category	Mapped domain	Mapped scale	Harmonised record
Citizen survey	"Extreme weather event (flood)" with accompanying report of "road closure" on a subsequent item	Environment (primary); Transport (cascaded)	Mid-scale	Env/Mid + Transport/Mid, severity 3
EM-DAT	Disaster type: "Flood"; meets inclusion thresholds (for example 100+ affected)	Environment	Large-scale	Env/Large, severity 4
Copernicus EMS	Activation category: "Flood"; rapid-mapping product issued	Environment	Large-scale	Env/Large, severity 4
Literature (SLR)	Coded as "flood-induced transport disruption" in the grounded-theory scheme	Environment (trigger); Transport (impact)	Large-scale	Env/Large + Transport/Large, severity 4

perceptions have accordingly been relocated to Supplementary Material S2.

Taxonomy ability to differentiate Table 6 ranks the ten most-experienced disruption categories in the weighted study sample. The table is presented not as a prevalence estimate, but as evidence that the taxonomy distinguishes between categories with sufficient granularity to produce a differentiated ranking when applied to citizen-reported data. Six of the ten most frequently reported categories fall within the Transport domain, two within Utilities, one within Environment, and one within Public Space, which is consistent with a classification structure that separates domains at an appropriate level of resolution for citizen-facing monitoring.

Table 6 Top ten disruption categories experienced by survey respondents under the proposed taxonomy (pan-European pilot, weighted; ESS ≈ 36). The table illustrates the ability to differentiate of the taxonomy when applied to citizen-reported data; it is not a prevalence estimate for European cities

Rank	Disruption category	Domain	%[a]
1	Road works / street closures	Transport	85.0
2	Public transport delays	Transport	62.9
3	Extreme weather events	Environment	61.3
4	Heavy traffic congestion	Transport	59.8
5	Digital connectivity outage	Utilities	57.1
6	Parking shortages	Transport	55.6
7	Traffic signal outages	Transport	45.1
8	Power outage	Utilities	44.1
9	Strikes (transport services)	Transport	36.9
10	Excessive noise	Public Space	36.8

[a] Weighted percentages from $n = 140$, ESS≈36. Indicative uncertainty range ±12–17 pp (approximate design-based indication, not a formal confidence interval); treat as illustrative indicators only

Respondents could report multiple disruption categories; percentages therefore do not sum to 100

Social media corroboration Normalised domain distributions from the social media dataset, covering the pilot cities, are summarised in full in the companion paper; in this paper, the data are used only to check whether the thematic prominence of Transport in the survey is echoed in online

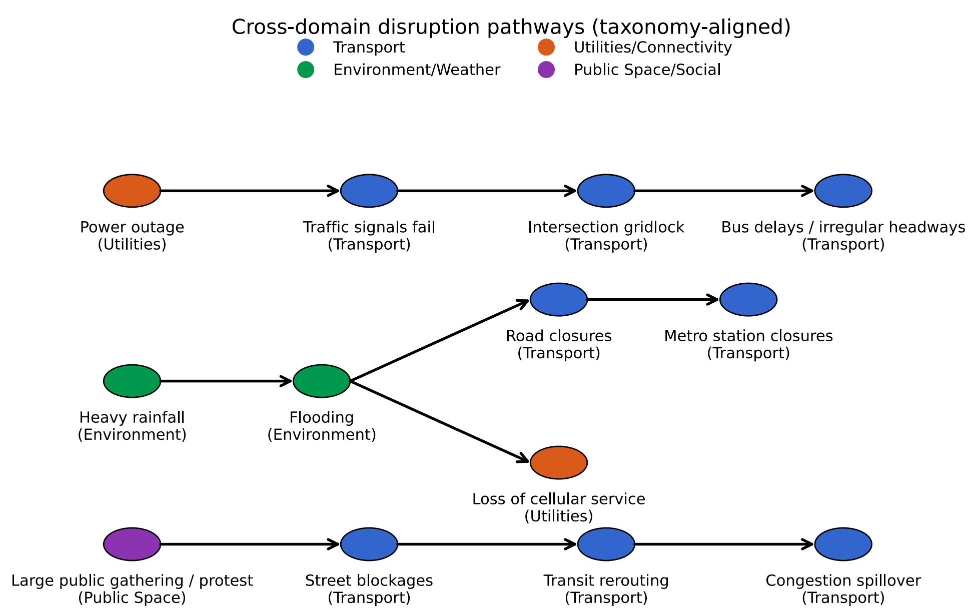


Fig. 3 Typical cross-domain disruption propagation pathways synthesised from literature review and survey narratives. Arrows indicate plausible, commonly reported propagation pathways relevant to early-warning and incident-management design; they represent reported co-occurrence patterns, not statistically validated causal sequences

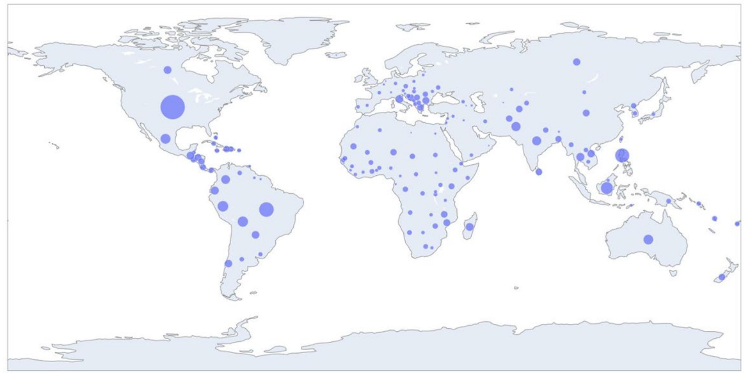


Fig. 4 Global disaster event distribution 2001–2025 from EM-DAT. The figure provides context for the large-scale end of the disruption spectrum, though temporal and spatial resolution differ from daily and mid-scale citizen-reported experiences

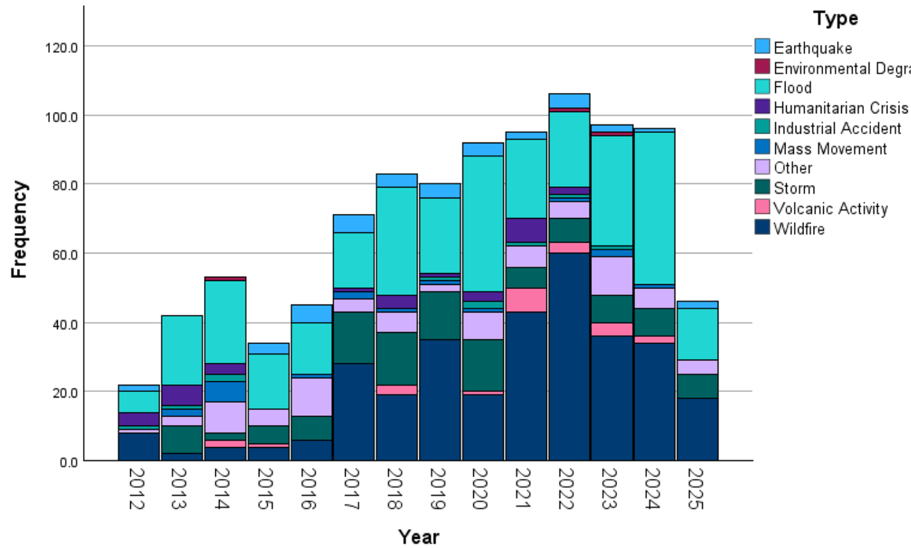


Fig. 5 Copernicus emergency management service activations by disaster type (2012–2025). Satellite-derived records anchor the large-scale end of the disruption spectrum and complement citizen-reported daily and mid-scale patterns

discourse. Transport consistently accounts for the largest share of classified posts across the pilot cities, which provides thematic, though not temporally aligned, corroboration of the survey pattern. The caveat remains that the social media data cover a different time window (May to August 2025) and a single platform, so this convergence should be interpreted as a thematic consistency check rather than as independent validation. Further detail is relegated to the companion paper because it is not essential to the methodological contribution advanced here.

EM-DAT and CEMS context Figs. 4 and 5 provide the large-scale disaster backdrop: EM-DAT global trends (2001 to 2025) and CEMS activations by disaster type.

These sources anchor the large-scale end of the spectrum and demonstrate the framework's capacity to span scales, from daily roadworks to regional floods, within a single taxonomic structure.

Thematic cross-source interpretation Across the three core sources, Transport is consistently the most salient disruption domain under the taxonomy. The literature synthesis identifies transport-related cascading failures as the most frequently studied pathway; the survey places six transport categories in the top ten; and EM-DAT and CEMS records, focused on large-scale events, confirm that floods and storms (Environment domain) are the primary large-scale mobility threats, whilst transport infrastructure failures feature prominently in cascading sequences. The consistency of these patterns across independently collected sources, despite their different temporal windows and methods, is consistent with the proposition that the taxonomy captures a recurrent thematic pattern in European urban disruption experience, though event-level confirmation will require temporally aligned data. The implication for sustainable mobility planning is that a common taxonomy can support cross-source narratives that city authorities can audit, even before event-level validation becomes feasible.

4.3 Preliminary design guidelines (RQ3)

This section addresses RQ3 by deriving a set of preliminary design guidelines from the pilot evidence. Each heuristic is grounded in a specific pattern observed in the data, and each is labelled as provisional, meaning that it is an informed

Table 7 Temporal distribution of disruption events from the pan-European pilot survey. The pronounced recency bias is consistent with the need for near-real-time monitoring in any future routine deployment

Timeframe	Number of events	Weighted percentage
Past week	937.1	38.45%
Past month	572.9	22.82%
Past 3 months	427.3	16.34%
Past 6 months	598.1	22.39%

Event counts are weighted; decimal values reflect post-stratification adjustment

Respondents could report multiple events; counts are event-level, not respondent-level

Table 8 Season-adaptive monitoring calendar derived from EM-DAT seasonal clustering (4,179 records, 2000–2025) and pilot survey temporal patterns. Thresholds are to be calibrated during future field deployment

Season	Priority hazard types	Recommended monitoring adjustment
Spring (Mar–May)	Floods, storms	Elevated flood-detection sensitivity; pre-positioned rerouting contingencies
Summer (Jun–Aug)	Heatwaves, wildfires	Activate heat-mobility coupling; wildfire evacuation routing on standby
Autumn (Sep–Nov)	Storms, floods	Elevated storm and surface-water monitoring; highest overall event frequency
Winter (Dec–Feb)	Snow/ice, cold spells	Ice-road and PT vulnerability alerts; lowest overall event frequency

Seasonal splits are descriptive baselines; significance testing is planned for the field phase

starting point for implementation specification rather than a validated system requirement.

Temporal recency patterns Survey respondents exhibited pronounced recency bias (Table 7): 38.5% of reported events occurred in the past week and 22.8% in the past month. This clustering is consistent with a pattern in which rapid-onset, short-lived events dominate citizen recall, and it carries direct implications for the frequency of any future routine monitoring.

The recency clustering motivates, but cannot by itself determine, the update frequency of a future monitoring capability: a high share of recently recalled events indicates rapid event turnover, not a specific refresh rate. Hourly updating is therefore put forward only as a candidate setting for future testing, to be evaluated against the detection-delay measure defined in Sect. 5.4.

Season-adaptive monitoring calendar Beyond the weekly recency pattern, analysis of the 4,179 EM-DAT records reveals a moderate seasonal signal in large-scale mobility-relevant hazards: summer accounts for 29% of events, autumn 25%, spring 23%, and winter 23%. Floods and storms cluster in spring and autumn; heat-related mobility degradation concentrates in summer; wildfire activity

Table 9 72-hour household emergency preparedness levels (pan-European pilot survey, weighted; ESS ≈ 36). Over 60% of households are slightly or not prepared, which establishes an illustrative deficit for future resilience monitoring

Preparedness level	% respondents	Cumulative %
Fully prepared	10.7	10.7
Well prepared	9.2	19.9
Moderately prepared	18.6	38.5
Slightly prepared	44.1	82.6
Not prepared	17.4	100.0

Indicative uncertainty range ±12–17 pp (not a formal confidence interval); treat as illustrative indicators only

peaks in late summer across European areas of interest. These patterns suggest the potential value of a season-adaptive alert calendar (Table 8), though the seasonal splits are descriptive and require significance testing during future field deployment.

Preparedness baselines Table 9 shows that over 60% of households describe themselves as only “slightly” or “not” prepared for a 72-hour emergency, which establishes an illustrative baseline deficit of relevance to any urban resilience strategy.

These baselines are a necessary precursor for tracking how communities respond to disruptions over time: to show that a system is learning, a starting point against which to measure change is required. Whether post-disruption surveys reveal rising preparedness or a shift toward proactive strategies is a question that requires repeated measurement and lies outside the present study. The implication for policymakers is that baseline preparedness deficits, even when indicative only, identify the population segments that any future communication campaign would need to target.

Coping strategies The following table is included to illustrate how the taxonomy enables coding of behavioural responses across the Coping facet; the specific percentages are pilot-stage indicators only. The coping item was a select-all-that-apply question posed to respondents who had described a most disruptive incident. Weighted percentages in Table 10 are expressed relative to the full weighted sample, with respondents who did not answer the item counted as not selecting a strategy, and they therefore sum to more than 100 across the nine tabulated strategies (137.5 in total). In the raw (unweighted) responses of the analysed sample, 49 of the 87 respondents who answered the coping item (56.3%) selected more than one strategy, with an average of 2.2 strategies per answering respondent; the most common combinations paired the proactive travel adjustments, namely changed travel mode with changed transport route, and changed travel mode with postponing or cancelling the trip. “Did nothing and waited” was presented as one option among others and could be selected alongside an active strategy, reflecting sequential or mixed responses within the

Table 10 Coping strategies reported by pan-European pilot survey respondents (weighted; ESS ≈ 36). Respondents could select multiple strategies, so percentages sum to more than 100. The predominantly reactive pattern and the high "did nothing" share (30.0%) are consistent with low baseline adaptive capacity

Rank	Coping strategy	Weighted %
1	Did nothing and waited	30.0
2	Postponed or cancelled trip/activity	20.1
3	Worked or studied remotely	17.1
4	Changed travel mode (walked, cycled, car-shared)	15.5
5	Sought information via app or social media	14.6
6	Changed transport route	13.7
7	Sought help from friends or family	13.4
8	Contacted service providers or authorities	7.0
9	Used a community-based solution (mutual aid)	6.1

Weighted percentages are expressed relative to the full weighted sample; respondents who did not answer the item are counted as not selecting a strategy

Table 11 Candidate design settings for future field testing, derived from pilot evidence. All values are candidates, not validated requirements

Parameter	Candidate value	Rationale	Source Evidence
Update frequency	Hourly	38.5% events <1 week old (motivating, not determining)	Survey (Table 7)
Historical horizon	12 months rolling (minimum)	Full annual hazard cycle; 6-month survey horizon insufficient for seasonal analysis	Survey + EM-DAT seasonal patterns
Spatial resolution	1 km^2 (urban)	European 1 km^2 statistical grid district scale	Literature Eurostat grid standard
Priority domain	Transport	6 of top 10 categories	Survey + corroboration
Severity scale	5-level ordinal	Sendai-aligned maps to EM-DAT	Crosswalk (Supp. Mat.)

All values are candidate settings for future field testing against the performance measures of Sect. 5.4; none is a validated requirement

same incident, for example waiting initially and rerouting once information became available; the questionnaire did not record the sequencing of strategies. In the raw responses it was selected by 31 respondents, of whom 19 co-selected at least one active strategy. A predominantly reactive pattern (30.0% did nothing and waited) and relatively low uptake of proactive responses (for example 15.5% shifted mode) are consistent with low baseline adaptive capacity, which would motivate real-time information tools in any future deployment.

Design heuristics summary Table 11 consolidates the preliminary design guidelines derived from the pilot evidence. Each entry is labelled as provisional and is linked to the specific pilot pattern that supports it. The table is intended as an informed starting point for implementation specification, not as a validated system requirement.

The survey instrument (Supplementary Material S2) offered four further response options that are not tabulated as coping strategies: adopted a new habit or routine that improved daily life (raw count 9 of the 87 answering respondents), discovered a more efficient way to handle similar situations (9), collaborated with others to find an alternative solution (10), and free-text Other (6). The first three record learning outcomes rather than coping actions and are analysed in the antifragility-oriented follow-on work; they are reported here by raw count for one-to-one correspondence with the instrument.

5 Discussion

The evidence from the three research questions is consistent with the guiding proposition at the level of applicability, feasibility, and thematic consistency across sources; since no alternative classification approach was evaluated, no claim of comparative enhancement is made. The domain-by-scale taxonomy, combined with the crosswalk tables, was applied consistently across four heterogeneous evidence streams (survey, literature, EM-DAT, CEMS), with supplementary corroboration from social media. Inter-coder reliability ($\kappa \geq 0.75$) was consistent with acceptable coding consistency. Thematic cross-source comparison revealed convergent patterns, most prominently the salience of transport disruptions, across sources that differ in method, temporal window, and spatial resolution. The taxonomy thus demonstrates its capacity to characterise urban events affecting mobility across heterogeneous sources in a pan-European pilot context.

It is necessary, however, to be explicit about what this evidence does and does not establish. The taxonomy's consistent applicability across sources ($\kappa \geq 0.75$) and the thematic convergence of domain-level patterns are demonstrated findings. The specific disruption frequencies and design parameters derived from the survey are illustrative only, constrained by an effective sample size of approximately 36. The design guidelines proposed in Sect. 4.3 are preliminary starting points, not validated implementation specifications. Full validation would require temporally aligned, longitudinal multi-source data and probability-based sampling at each site, and independent replication of the coding by research teams outside the present study.

RQ1: *Taxonomic harmonisation* The two-facet (domain-by-scale) taxonomy with standardised crosswalk tables was applied consistently across multiple heterogeneous sources whilst preserving each source's specific characteristics. Inter-coder reliability ($\kappa \geq 0.75$) is consistent with coding consistency across the crosswalk. The Urban Event Catalogue (76 events) and the worked example (Box 1) together illustrate that the taxonomy can be applied in practice to produce harmonised event records that are auditable end to end.

RQ2: *Disruption patterns and cross-source consistency* Transport disruptions were the most salient domain across citizen-facing sources: 85% of survey respondents reported roadworks, and transport accounted for the largest share in the social media corroboration data. Environment ranked second across sources. Whilst temporal misalignment prevents matching specific events across streams, the thematic convergence is noteworthy given how different the sources are in method and coverage. All survey figures are illustrative indicators (ESS $\approx$ 36).

RQ3: *Preliminary design guidelines* Pilot evidence motivates four candidate settings: (i) hourly updating, since 38.5% of events were reported within the past week, whilst recognising that recall shares alone cannot determine a refresh rate; (ii) rolling windows of at least twelve months, since a complete annual hazard cycle cannot be captured in less; (iii) 1 km^2 spatial resolution in urban cores, aligned with the standard European statistical grid; and (iv) Transport as the initial priority domain. These are candidate settings for future testing, not validated recommendations, and site-specific calibration will be needed at each site.

5.1 Methodological contributions and replicability

The framework's value lies in its replicable infrastructure for integrating multiple disaster risk reduction evidence streams, with direct relevance to how cities may in future monitor and plan for sustainable mobility. Three elements are transferable.

Standardised taxonomy and crosswalk tables Other researchers and city authorities can adopt the domain-by-scale taxonomy and adapt the crosswalk mappings to their own data. The taxonomy balances enough granularity for applied decisions against enough simplicity for manageable coding. Crosswalk tables with detailed coding rules are provided as Supplementary Table S1.

Honest treatment of data limitations Rather than obscuring the low effective sample size or the temporal gaps between sources, the paper reports them as inherent features of early-stage multi-source work. This transparency sets realistic expectations and provides a methodological benchmark for comparable pilots.

Thematic versus temporal cross-source comparison By separating what thematic comparison can deliver now from what event-level temporal matching will require, the paper clarifies the current reach of multi-source synthesis at different stages of data maturity.

5.2 Comparative positioning

The observation that Transport is the most salient disruption domain in citizen experience (85% reporting roadworks; 62.9% reporting PT delays) is consistent with Liu et al. (2023) finding that mobility disruptions compound other stressors across urban settings. The 15.5% mode-shift adoption rate provides a European illustrative figure that can be compared, cautiously given cultural and infrastructure differences, with Yabe (2021) Japanese recovery data. Unlike the satellite-centred framework of Zafeiropoulos et al. (2023), the present approach extends to citizen-generated evidence, responding to calls in the literature for ground-level input in disaster risk reduction monitoring, though full ground-truth validation remains a task for future longitudinal deployment.

The multi-source strategy also parallels the approach of Barbero et al. (2023), who combined questionnaires, interviews, use cases, and workshops to investigate training and energy efficiency across Europe, and structured their discussion around named themes corroborated from multiple instruments. The present framework applies a similar logic to urban disruption mapping, with the taxonomy and crosswalk tables providing the methodological bridge between instruments. Of particular interest is that, whilst Barbero et al. proceeded by thematic convergence without an explicit classification artefact, the present paper adds such an artefact (the taxonomy and crosswalk tables) to the shared strategy.

5.3 Implications for system design

The design settings that follow are candidate values derived from pilot-stage evidence; they are put forward for testing against the performance measures set out in Sect. 5.4, not as validated system requirements. Three candidate parameters for future implementation follow from the pilot findings:

1. Update frequency: The pronounced recency bias (38.5% of events within the past week; Table 7) motivates, but cannot by itself determine, a sub-daily update cycle. Hourly updating is proposed as a candidate setting to be tested against the detection-delay measure defined in Sect. 5.4.
2. Historical horizon: A rolling window of at least twelve months is proposed as the candidate setting, since a complete annual hazard cycle (Table 8) cannot be captured in a shorter window. The six-month recall horizon of the pilot survey was insufficient for annual-cycle analysis and is not carried forward as a design value.
3. Spatial resolution: A 1 km^2 grid in dense urban cores is proposed as the candidate setting because it aligns with the standard European 1 km^2 statistical grid used by

Eurostat and INSPIRE (Eurostat 2026; INSPIRE Thematic Working Group Coordinate Reference Systems and Geographical Grids 2014), which eases population weighting and cross-city comparability, and because it approximates typical district scales whilst maintaining sufficient data density. Coarser resolution in suburban and rural zones balances detail against data availability.

These candidate settings appear feasible for pan-European application, subject to the field testing set out in Sect. 5.4, and offer a provisional temporal and spatial framework for developing future disruption indicators. The implication for urban managers is that a minimal set of coding decisions, frequency, horizon, resolution, priority domain, can be provisionally taken on the basis of pilot evidence whilst awaiting full validation.

5.4 Validation roadmap for temporal triangulation

The future validation referred to throughout this paper can be specified along four elements, so that the criteria for judging a future deployment are explicit in advance of data collection.

Event matching across sources Events would be matched in time and space using scale-dependent tolerances: candidate matching windows of ±6 h for Daily-scale, ±24 h for Mid-scale, and ±72 h for Large-scale events, combined with spatial buffers tied to the scale facet (street-segment or stop-level for Daily, district-level for Mid-scale, and event-footprint polygons, such as CEMS rapid-mapping products, for Large-scale events). All records would first be geocoded to a common spatial reference, a 1 km^2 grid nested within NUTS-3 units, so that citizen reports, database entries, and satellite footprints can be intersected. These tolerances are themselves candidate settings, to be tuned during the field phase.

Duplicate and conflicting reports Multiple reports of the same event would be resolved into a single canonical event record. Deduplication would proceed by clustering records that fall within the same spatio-temporal window and share a trigger-domain label. Conflicting attributes, for example diverging severity assignments, would be retained as fields on the canonical record and resolved by a documented precedence order: official incident logs over satellite products over citizen reports for event occurrence and location, with citizen reports privileged for experienced mobility impact. Unresolved conflicts would be flagged for dual-coder adjudication.

Reference standard The reference standard would be an adjudicated event register for each focal city, constructed from road-authority and public-transport incident logs together with CEMS activations, coded independently by two coders with adjudication of disagreements. This register would serve as the ground truth against which detection from surveys and social sensing is scored.

Performance measures Performance would be reported as: inter-coder agreement (Cohen's κ) on crosswalk application; precision, recall, and F1 of event detection against the reference register; detection delay, measured as the time from event onset in the register to first detection in each stream; spatial matching error, measured as the distance between detected and reference locations; and replication of the full coding pipeline by independent research teams and in further cities. Together, these elements convert the general appeal to "future validation" into a testable protocol.

5.5 Transferability to other disruption contexts

Although developed for urban mobility, the framework separates elements that are reusable as they stand from elements that are context-bound. The reusable elements are the two-facet (domain-by-scale) classification logic; the crosswalk-table method with documented coding rules and dual-coder reliability testing; the integration workflow of Fig. 2; and the distinction between thematic cross-source comparison and temporal triangulation. These could transfer with little change to related settings such as utility outages, emergency service access, freight and logistics disruption, public health emergencies, and major public events, each of which involves heterogeneous evidence streams (official logs, citizen reports, satellite or sensor data, and academic literature) that require harmonisation before analysis.

The context-bound elements are the specific domain categories, the severity anchors of Table 3, the scale thresholds, and the source-specific crosswalk mappings. A freight application, for example, would require domain categories reflecting terminal, corridor, and border-crossing disruptions, with severity anchors expressed in throughput or dwell time rather than passenger delay; a public-health application would require scale bands tied to administrative response levels rather than spatial footprints alone. Transferring the framework therefore means re-deriving the categories and thresholds through the same documented procedure, including dual-coder reliability testing, rather than copying the mobility-specific content.

5.6 Limitations

Six limitations bound the interpretation of the pilot findings.

1. *Survey representativeness* Post-stratification weighting reduced the effective sample size to approximately 36, which rules out population-level inference. The results demonstrate that the taxonomy can be applied

across diverse settings, but they should not be read as prevalence estimates for European cities. Future implementations should target ESS ≥ 200 per site through probability-based sampling.

2. *Temporal misalignment* The social media window (May to August 2025), survey retrospective periods (variable), EM-DAT records (2000 to 2025), and CEMS data (2012–2025) do not overlap for the same mobility events at focal sites. Thematic comparison remains valid, but event-level validation will require a sustained period during which all streams collect data concurrently.
3. *Platform-specific biases* Social media data reflect the demographics and discourse norms of a single platform, with English over-represented at 21.1%. Cross-source comparison with survey and official data partially counterbalances but does not fully resolve this issue. Platform application programming interface rate limits and processing delays (5–10 min) introduce additional sampling and latency biases.
4. *Pilot-stage baselines require longitudinal follow-up* The present study establishes illustrative baseline patterns; longitudinal monitoring is needed to assess how disruption response evolves over time. Whether preparedness improves or coping strategies diversify are questions that require repeated measurement over 12 to 24 months of aligned multi-source data.
5. *Classification validity and independent replication* The taxonomy design has been tested for thematic consistency and inter-coder reliability within the present research team, but not for predictive validity or for sensitivity to reclassification by domain experts outside the team. Independent replication by other research groups, ideally applying the crosswalks to fresh data from further European pilot sites, would strengthen confidence in the classification structure.
6. *Literature corpus restricted to Q1 journals* The Q1 eligibility criterion applied in the systematic literature review introduces publication and disciplinary bias: emerging journals, practitioner and grey literature, and regional outlets are excluded, so the literature-derived categories may under-represent disruption types documented mainly outside Q1 venues. The crosswalk method itself is indifferent to corpus composition, and future applications of the taxonomy can relax this criterion.

6 Conclusions

This study has developed a methodological framework for pan-European urban event mapping designed to support evidence-based planning for sustainable urban mobility. Three contributions emerge.

First, the paper presents a *replicable two-axis taxonomy with published crosswalk methodology* for harmonising diverse disruption data sources. The domain-by-scale taxonomy, supported by coding rules and crosswalk tables (Supplementary Table S1), achieved inter-coder reliability of $\kappa \geq 0.75$ and was successfully applied across citizen surveys, a systematic literature review, EM-DAT disaster records, and Copernicus EMS satellite activations.

Second, the paper offers a *transparent multi-source integration workflow* with honest treatment of early-stage limitations. By clearly distinguishing thematic cross-source comparison (feasible with current data) from temporal triangulation (requiring sustained longitudinal data), the methodology sets realistic expectations for what multi-source synthesis can deliver at different stages of data maturity.

Third, the paper provides *illustrative pilot patterns and preliminary design guidelines* that may inform, but do not yet validate, the specification of future field monitoring systems. The pronounced recency bias (38.5% of events within the past week), the salience of the Transport domain (six of the top ten disruption categories), and the low preparedness baseline (only 19.9% reporting high preparedness) are consistent with preliminary guidelines on update frequency, domain prioritisation, and citizen-engagement strategies. Full field validation will require a longitudinal follow-on study with temporally aligned data from all sources over a sustained period (12 to 24 months), together with probability-based sampling (ESS ≥ 200 per site) and independent replication of the coding by research teams outside the present study.

RQ1 (Taxonomic harmonisation): The two-facet taxonomy with standardised crosswalk tables harmonises heterogeneous data sources whilst retaining source-specific characteristics. Inter-coder reliability ($\kappa \geq 0.75$) is consistent with acceptable coding consistency.

RQ2 (Disruption patterns): Across a pan-European sample, Transport disruptions were thematically the most salient domain: 85.0% of survey respondents reported experiencing roadworks and 62.9% public-transport delays. Temporal misalignment between sources means these are thematic rather than event-level findings. Results should be interpreted as illustrative indicators (ESS ≈ 36), not population estimates. The low ESS constrains the interpretability of survey-derived percentages; the study mitigates this limitation by combining survey evidence with literature synthesis, official event databases, and supplementary social media corroboration.

RQ3 (Preliminary design guidelines): Pilot evidence motivates hourly updating, rolling windows of at least twelve months, 1 km^2 urban resolution, and Transport-domain prioritisation as candidate settings for future field testing, not as validated recommendations; the criteria for that testing are set out in Sect. 5.4.

A further limitation concerns the survey component. Post-stratification weighting reduced the effective sample size to 36, which limits the robustness of survey-based estimates and rules out population-level inference. The study does not, however, rely on the survey in isolation: its conclusions are based on cross-source comparison across multiple evidence streams, including the systematic literature review, official event databases, and supplementary social media data. The survey should therefore be interpreted as one component of a broader multi-source methodological design.

Four directions for future research follow from this pilot study. First, a longitudinal follow-on study should collect time-aligned data from all sources over a sustained period (12 to 24 months), so that temporal triangulation through event-level cross-validation becomes feasible, following the matching rules, reference standard, and performance measures set out in Sect. 5.4. Second, future survey implementations should adopt probability-based sampling with ESS $\geq$ 200 per focal site to support population-level inference. Third, the taxonomy and illustrative baselines established here provide the prerequisite infrastructure for future assessment of how urban mobility systems respond to, and learn from, disruptions, including metrics for delay-variance reduction, mode-shift capacity, and coping-repertoire diversity. Fourth, a companion paper will present the social media analytics framework in full, including the natural language processing classifier, cross-border information flow networks, and temporal discourse analysis that lie beyond the scope of the present taxonomy paper.

Use of AI-assisted tools: During the preparation of this work, the authors used AI-assisted tools to help with language editing and to improve clarity and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Data availability Aggregated summary statistics are included in the manuscript and figures. The event taxonomy crosswalk table (Supplementary Table S1) and the full survey instrument (Supplementary Material S2) are available as supplementary materials. The Urban Event Catalogue is available from the corresponding author on reasonable request. Raw survey data cannot be shared publicly in accordance with GDPR and ethical approval conditions. EM-DAT data are publicly available at https://www.emdat.be; Copernicus EMS data at https://emergency.copernicus.eu.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethics approval and consent to participate This study involved an anonymous, voluntary online questionnaire completed by adults aged 18 or over. Informed consent was obtained via a mandatory consent screen; no names, contact details, or other directly identifying information was collected, and responses are reported only in aggregate. Ethics requirements for human participation were addressed under Horizon Europe Grant Agreement No. 101203052 (AntifragiCity), through the project's Ethics Deliverable on Human Participants (Ethics Requirement No. 1), submitted to the European Commission, and implemented via the project's Data Management Plan (Deliverable D1.3). Social media data comprised publicly available posts processed under data minimisation, retaining only a generic identifier, timestamp, and post text; all analyses are reported in aggregate.

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