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Blending Efficiency and Resilience in the Performance Assessment of Urban Intersections: A Novel Heuristic Informed by Literature Review

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Abstract: Urban mobility underscores the vital importance of ensuring traffic efficiency on road segments, intersections, and transportation networks, especially in challenging circumstances. In this perspective, the essential approach to improving urban intersection efficiency should involve understanding critical factors for maintaining operational performance in the face of disruptions such as storms. This paper, inspired by a systematic literature review, presents a novel heuristic for evaluating urban intersection efficiency, with resilience as its guiding principle. The methodological path was designed to address the fundamental question: How can urban intersections be designed and managed to ensure efficiency and resilience in the face of disruptions? Drawing inspiration from the Highway Capacity Manual procedure, the methodological approach encompasses both pre-storm and post-storm scenarios, comparing delay times at roundabouts and signalized intersections before and after a storm. The results reveal significant changes in delay times for traffic signals, although the choice between roundabouts and signalized intersections should be context-specific, considering factors like traffic conditions, resilience requirements, and associated trade-offs. By shedding light on the interplay between intersection design, control strategies, and urban resilience, this research provides valuable insights into integrating resilience considerations into intersection performance assessment and management strategies. It also underscores how particular intersection designs can impact efficiency and recovery, essential considerations when assessing whether a road or intersection project is resilient.

Keywords: road geometric design; resilient road; urban mobility; road traffic assessment; roundabout; traffic signal; performance efficiency

Citation: Zare, N.; Macioszek, E.; Granà, A.; Giuffrè, T. Blending Efficiency and Resilience in the Performance Assessment of Urban Intersections: A Novel Heuristic Informed by Literature Review. *Sustainability* **2024**, *16*, 2450. https://doi.org/10.3390/su16062450

Academic Editors: Yusheng Ci, Lina Wu and Ming Wei

Received: 3 February 2024
Revised: 8 March 2024
Accepted: 13 March 2024
Published: 15 March 2024

1. Introduction

Resilience is closely tied to the Sustainable Development Goals (SDGs) outlined in the 2030 Agenda [1], particularly SDG 11, which emphasizes building resilient cities and communities. In this context, resilience involves creating adaptive urban road infrastructure and sustainable systems capable of withstanding environmental and social challenges. Integrating resilience into sustainable development practices also contributes significantly to achieving other goals, notably supporting sustainable mobility for people [2]. In the pursuit of the above objectives at the international level, there has been significant development, testing, and enhancement of resilience assessment methods across diverse contexts [3]. These efforts can provide decision-makers at multiple levels, from local to national, and other stakeholders, with greater data and tool accessibility. However, a significant dearth of evidence-based analysis persists in existing assessment tools, while systematic and comprehensive resilience assessment approaches remain underutilized, especially for urban areas and intricate road infrastructure [4,5].

Resilience, comprehensively, refers to the capacity of urban systems, including socio-ecological and socio-technical networks across temporal and spatial scales, to sustain their intended functions amid disruptions [6]. It surpasses mere adaptation, involving transforming systems to enhance adaptive capabilities [6]. This concept emphasizes the swift restoration of equilibrium post-shock, highlighting efficiency in withstanding and adapting to forthcoming challenges [7]. In the realm of road infrastructure, resilience refers to the capacity to adapt, endure, and transform amid external threats like natural disasters and internal challenges such as heightened traffic demands [8,9]. Road resilience entails the ability to restore functionality after disruptions to the transportation system. Conversely, vulnerability on roads and intersections stems from susceptibility to harm caused by shifts in traffic patterns, land use, and climate conditions [7,8]. Inadequate adaptation, an inability to manage shifting conditions, and limited resilience heighten risk and compromise the well-being and safety of road users within transportation systems [10]. Unlike resilience, efficiency in road infrastructures usually refers to their ability to transport people or goods effectively and reliably, minimizing time, costs, energy, and environmental impacts [5,11,12]. Emphasizing efficiency in road infrastructure entails optimizing performance and minimizing adverse effects to effectively and sustainably meet user and societal needs [7,13].

The existing literature on this topic features studies assessing current resilience at country, regional, or city levels against disasters such as floods, storms, hurricanes, and earthquakes [7,14,15]. Various methodologies, including indicators, indices, and conceptual frameworks, have been developed and employed in case studies [9,16–18]. For instance, the "R4" resilience triangle framework addressed recurrent congestion as an internal disruption on urban roads, using spatial-temporal traffic patterns compared with other freeways and signal-controlled arterial roads [9]. While the proposed metric effectively captured congestion patterns from a resilience perspective, further extensive research is required, covering diverse scenarios in varying traffic conditions. Studies [16,17] employed an adaptive strategy for traffic signal control to address disruptions at intersections, enhancing resilience by adjusting control plans during crashes. This led to a reduced overall delay time compared to conventional signal plans. However, further research is still necessary to expand the analysis to encompass diverse intersection geometries and traffic conditions.

Few studies have centered on urban road network nodes, primarily highlighting network-level resilience evaluation [18]. Despite striving for daily mobility safety, traditional road designs prioritizing efficiency may falter during unforeseen events [19,20]. The same applies when assessing whether a road or intersection project is resilient. Intersections, as critical elements, require a comprehensive assessment to gauge their resilience. Balancing resilience enhancement and efficiency optimization in urban planning and road infrastructure upgrades is paramount [21,22]. Understanding the trade-offs between these factors is an ongoing challenge. In this view, implementing resilience in the performance efficiency assessment of urban intersections is the specific gap in the literature that the paper aims to fill.

The Purpose of the Study

This paper introduces a novel heuristic for evaluating urban intersection efficiency, with resilience as its guiding principle. The necessity of the method stems from a systematic literature review that used common expressions consistent with the specific topic, such as 'resilient roads', 'urban mobility', 'intersection efficiency', 'traffic congestion', and 'connected infrastructure', deemed useful by the authors to delimit the research motivations and outline its societal and scientific contribution. Despite acknowledging the limitations of our literature review, it nevertheless effectively enabled a thorough analysis and synthesis of existing research on the specific topic. To describe the contents, the key points of the study are listed as follows:

- The review summarized key findings, explored synergies in the selected research, identified knowledge gaps, and highlighted prevalent subjects through thematic analysis. Overall, it critically examined existing work, offering insights for further investigation.
- Identifying various urban intersection types, the study conceptualizes alternative layouts or control modes to address a fundamental question: 'How can urban intersections be designed and managed to ensure efficiency in the face of future disruptions?'. However, this also requires conducting a resilience assessment for each intersection layout or control mode, considering responses to natural or human-caused disruptions, evolving traffic conditions, and the specific context of each case.
- The approach proposed in this paper is inspired by the Highway Capacity Manual procedure [13], encompassing pre-storm and post-storm scenarios. Real-world urban road intersections are examined, envisioning their functionalities to address the specific question: 'How might the geometry or control mode of different intersection projects impact efficiency and resilience before and after a storm-related disruption?'
- It is assumed that a storm-induced power outage could adversely affect the intersection's efficiency and resilience [2,6,8,13,19]. The selected metric for assessing two intersection types (roundabouts and signalized intersections) in pre- and post-storm scenarios was the average control delay time. Defined as "additional travel time experienced by a driver, passenger, or pedestrian" [13], it measured performance.
- The scenarios were explicitly defined as follows:
  (1) In the pre-storm situation, the performances of roundabouts and signalized intersections were compared;
  (2) In the post-storm scenario, the comparison shifted to roundabouts and two-way stop-controlled (TWSC) intersections. Essentially, intersection efficiency was evaluated by comparing roundabouts to traffic signals before a storm, while intersection resilience was assessed by comparing roundabouts to stop signs after a storm. It was assumed that traffic signals could function as stop signs post-disruption [19]. Therefore, the average delay times of roundabouts and signalized intersections were compared to assess their relative efficiency under standard conditions, excluding extreme events or disruptions. In a post-storm scenario where road obstructions are possible and traffic lights operate as stop signs, we compared the average delay times of roundabouts and TWSC intersections to assess their resilience in the face of disruptions.

The study underscored the necessity of a flexible evaluation methodology that seamlessly integrates resilience and efficiency. The proposed heuristic approach drew insights from the literature, outlining a methodological trajectory adaptable to various intersection design scenarios. It represents a scientific contribution to intersection project assessment and optimization. Figure 1 illustrates the methodological approach adopted in this paper. The suggested approach involved measuring delay times at roundabouts and signalized intersections pre- and post-storm, revealing significant changes in traffic signal delay times. These findings provide valuable guidance for future road traffic management strategies, aiding in the selection of intersection types that uphold stability during disruptions and bolster resilience. Moreover, the research's social contribution offers critical insights into the relationship between intersection design, control strategies, and urban resilience, enhancing considerations for transportation infrastructure design and management.

After the introduction, Section 2 outlines the systematic literature review pertinent to the topic. Subsequently, Section 3 elaborates on the materials, methodologies, and findings of the examined case studies, while Section 4 delves into the preliminary results. The paper concludes by summarizing key findings and insights in the final sections, along with proposing future developments.

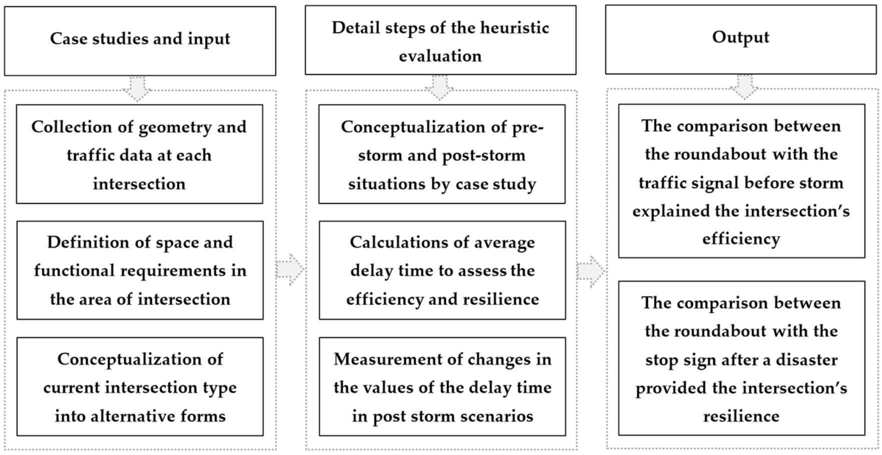

Figure 1. The proposed heuristic evaluation to assess resilience-oriented performance efficiency at urban intersections.

2. Literature Review

In contexts undergoing transitions, a literature review was conducted to identify contemporary methods for assessing the performance efficiency of urban road intersections from a resilience perspective. The review highlighted key factors, potential synergies, and challenges specific to transitioning environments. A screening process utilizing keywords from articles and their abstracts was employed to assess document relevance. Furthermore, papers were evaluated based on their inclusion in specific databases, ensuring a comprehensive exploration of the subject matter within evolving contexts. While acknowledging insights from the excluded gray literature, the research conducted a targeted assessment of factors influencing road intersection efficiency from a resilience perspective, focusing on peer-reviewed papers published since 2013 and searching for relevant information on various journal websites. To select the papers, we were inspired by the step-based research method outlined in [23]. The review narrowed the literature to no more than fifty papers, following a hybrid approach of meta-synthesis and realist review. It unfolded in three stages, concentrating on the qualitative content of the identified papers.

In the first phase, we conducted a 'title, abstract, and keywords' search within the Scopus database. Using only the terms 'resilient roads' and 'urban mobility', we identified in the dataset above 32 peer-reviewed articles as of 16 January 2024. Subsequently, we expanded the search by adding terms one at a time, including 'resilient roads', 'urban mobility', 'intersection efficiency', 'traffic congestion', and 'connected infrastructure'. Despite introducing these additional terms, no new papers were found by the indicated date. As a result, the five key terms of our search remained 'resilient roads' and 'urban mobility', along with 'intersection efficiency', 'traffic congestion', and 'connected infrastructure'.

During the second phase, the abstracts of all papers were scrutinized and assessed for relevance, potentially leading to exclusions. This screening process resulted in excluding four papers that did not meet the specified criteria and topic. Conference papers, books, or book chapters were retained, as there was no evidence of potential duplicates. In the third phase, a hybrid search approach was also employed, combining the reference list to discover additional papers initially overlooked. This method involved keyword-based searches, semantic searches, and other techniques for a more comprehensive collection of relevant information. This step revealed an additional 17 papers that blended efficiency and resilience in the performance assessment of urban intersections. Consequently, a total of 45 papers were thematically identified and ordered based on the following thematic analysis (see Section 2.1).

After reviewing papers, five key themes emerged in the third step of the research, although not without inevitable overlaps among them. The thematic analysis allowed the identification and discussion of these themes. While acknowledging the limitations of the review, the subsequent analysis allowed us to emphasize and discuss the main findings in the following sections. Figure 2 illustrates graphs detailing the number of papers identified each year in the search steps, encompassing both the Scopus-based search and the hybrid search, with incomplete years omitted.

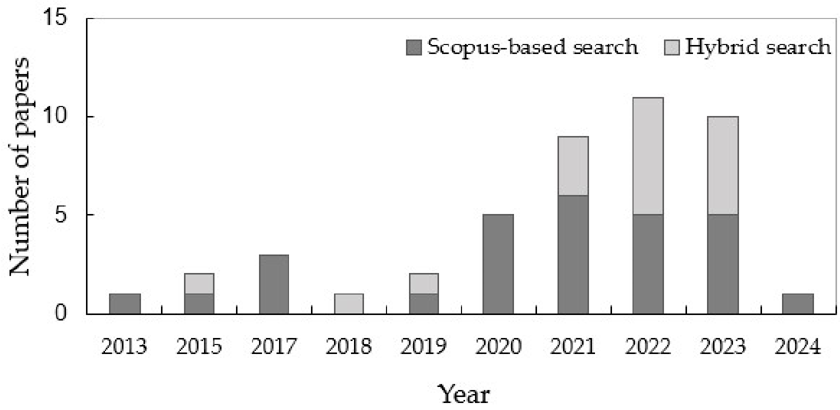

Figure 2. Graphs depicting the number of papers identified in the search step using Scopus and employing a hybrid search approach by year.

2.1. Defining Themes from the Reviewed Papers

This section outlines primary topics extracted from the literature, representing prevalent subjects identified through thematic analysis. The five main clusters included:

- Resilient Road Infrastructure Design (18 papers) [22,24–40];
- Connected Infrastructure and Intelligent Transportation Systems (8 papers) [41–48];
- Dynamic Traffic Management and Adaptive Signal Control (7 papers) [9,49–54];
- Urban Mobility Planning and Policy (5 papers) [55–59];
- Community Engagement and Behavioral Studies in Urban Mobility (7 papers) [60–66].

Table 1 shows papers by theme and Scopus-based search or hybrid search. Threads across many papers without aligning with a specific thematic area were also identified. Section 2.2 explores these threads, considering opportunities, challenges, and implications for integrating efficiency and resilience in the performance assessment of urban road intersections.

Table 1. Themes identified through thematic analysis.

Theme		References	
		Scopus Search *	**Hybrid Search ****
(1)	Resilient Road Infrastructure Design	[22,25–28,31,34–36]	[24,29,30,32,33,37–40]
(2)	Connected Infrastructure and Intelligent Transportation Systems	[41–45,48]	[46,47]
(3)	Dynamic Traffic Management and Adaptive Signal Control	[9,49–51]	[52–54]
(4)	Urban Mobility Planning and Policy	[55,58,59]	[56,57]
(5)	Community Engagement and Behavioral Studies in Urban Mobility	[60–64]	[65,66]

* Peer-reviewed papers searched in the Scopus database through a ‘title, abstract, and keywords’ search. ** There are references searched in a hybrid approach where papers were manually searched on some journal websites using keyword-based searches and semantic searches.

2.1.1. Resilient Road Infrastructure Design

Resilient roads should demonstrate durability, swiftly recovering from disruptions [24]. Their strength enhances urban safety and functionality, effectively addressing mobility challenges [25–28]. However, the research question, "What design features enhance the resilience of roads and facilitate quick recovery from damage caused by both man-made events and natural disasters?" remains open. This may be attributed to the absence of tools for assessing the performance efficiency of road infrastructure that incorporate measures of resilience suitable for various situations.

Integrating resilience into intelligent transportation is crucial, emphasizing the proactive role of human and artificial intelligence in mitigating disruptions, especially in developing economies [29]. This integration should enhance transportation resilience amid global warming challenges, emphasizing its significance for urban sustainability and efficient transportation systems [30–33]. However, studies have emphasized the importance of taking a proactive approach to crafting resilient road infrastructure. This involves delving into design principles that consider urban structure, alignment, cross-section, materials, and surfaces [28,34].

Shafiei-Dastjerdi and Lak [32] established a link between urban resilience and design, creating an operational framework for evaluating resilience at meso- and micro-scales. This qualitative approach provided methodological guidance for assessing urban form resilience, inspiring further research, particularly in rapidly developing historic urban areas. In turn, Sharif [33] explored urban streets as pivotal components of urban form, categorizing measures into network topology, design, and orientation. While offering insights into designing resilient streets and networks, it is advisable that future research should also explore pedestrian and vehicular movements, as well as connectivity implemented by road intersections, for a comprehensive understanding of urban resilience.

Prioritizing walking is crucial for sustainable cities, aligning with global decarbonization goals, and fostering cohesive communities. However, sidewalks, a planning priority, face neglect in car-centric urbanization. The lack of global sidewalk data and coordination challenges hinder the systemic understanding of walking's impact. Rhoads et al. [27] stressed the need for a broader discussion within the context of urban multi-modal mobility due to coordination challenges in pedestrian mobility compared to cars. Kirova and Markopoulou [28] developed a privacy-focused tool that used surface-based capacitive sensing for GPS-free pedestrian activity monitoring in public spaces. The simulation depicted spatio-temporal pedestrian behavior, providing anonymized large-scale information through dynamic maps, trend prediction, and insights to identify areas with high pedestrian density. Despite implementation costs, the research underscored the computational workflow's efficacy in mapping streets where additional space for pedestrians should allow safe use of public space. Future research efforts should concentrate on expanding the use of simulations and predictive modeling for a comprehensive understanding of pedestrian paths.

Despite the increasing popularity of resilience in complex systems, methods to enhance resilience in road networks and infrastructure systems remain uncertain. Yang [30] proposed a design strategy to improve energy efficiency in urban areas by altering their physical structure. However, persistent constraints in urban energy research from cognitive barriers across disciplines need deeper investigation. There is also a need to explore road performance endurance and recovery from disruptions [24,31,35]. McDaniels et al. [35] proposed a prioritization approach for disaster-resilient cities, emphasizing the value of information in decision analysis. In turn, Hettiarachchi et al. [24] suggested a paradigm shift in urban stormwater management to assess green infrastructure efficacy in warmer climates. Ilbeigi and Meimand [31] examined post-disaster transportation networks using NYC taxi GPS traces after Hurricane Sandy, revealing perturbed traffic patterns impacting network topology and performance. According to [34], road users can co-produce the mobility system, influencing infrastructure resilience while preserving historical habits and cultures.

From this perspective, the pandemic offered an opportunity to shift from a car-centric to a smart and sustainable transport system. In this regard, promoting cycling-friendly initiatives, 30 km/h zones, and traffic-calming solutions can further contribute to overall road infrastructure resilience [34,36].

The literature review also focused on intersection design considerations. The topic involves specific types, control modes, lane configurations, and traffic situations for optimal functionality and safety [22,37]. Zhao et al. [22] conducted a spatio-temporal analysis, enhancing our understanding of dynamic interactions between crowd movements and urban transportation infrastructure. The study highlighted the necessity for a thorough examination of temporal and spatial characteristics in urban road intersections for resilience-guided assessments, which is currently lacking in studies. In turn, Pratelli et al. [37] introduced a simulation-based methodology for identifying critical intersections for optimizing road networks' resilience under different traffic conditions. Roundabouts proved more robust, quickly restoring performance after disruptive events.

In the comprehensive exploration of the efficiency of urban road intersections from a resilience perspective, a prevalent concept is the 'challenge', often linked to insufficient data and assessment tools [38,39]. Additional research is addressing the infrastructure-related needs of autonomous vehicles, their impact on road infrastructure, prerequisites for safe operation, and the alignment of infrastructure with emerging technologies [40]. In this view, Mattinzioli et al. [38] introduced a comprehensive roadmap addressing critical research topics related to electric vehicles (EVs) and pavement degradation. Given the transformative impact of EVs on the transportation sector, continuous updates are crucial as vehicle fleets evolve, necessitating ongoing investigation by transportation engineers. While there has been extensive exploration of autonomous vehicles and their implications and benefits, the understanding of their impact on physical infrastructure is still in its early stages. Sharafeldin et al. [39] identified significant roadway characteristics influencing crash severity, emphasizing the often-overlooked variable of pavement friction, while Othman [40] delved into geometric design and pavement considerations to uncover changes and challenges introduced by autonomous vehicles. Autonomous vehicles exhibit the potential to offset human driver characteristics, influencing lateral clearance and vertical curve lengths. Specifically, Othman [40] emphasized that autonomous vehicles, reacting faster than humans, notably reduce sight stopping and decision sight distances, with driver behavior significantly influencing geometric design. The transformative impact on geometric design is evident in a potential lane width reduction to 2.4 m, with economic and environmental benefits. Challenges may arise in mixed-traffic scenarios with human-driven vehicles, impacting road capacities and pavement performance. Future roads should integrate technologies like embedded magnets and on-road charging, which require further research with reference to construction and maintenance costs.

The synthesis of findings from 18 papers on 'Resilient Road Infrastructure Design' underscores the necessity for future research to progress in integrating resilience into performance assessment and establishing a well-defined methodology for practical implementation.

2.1.2. Connected Infrastructure and Intelligent Transportation Systems

In recent years, there has been a heightened focus on the development of a multimodal transport system that addresses environmental concerns in rapidly urbanizing areas. This system seeks to offer the convenience associated with private cars. Research efforts on connected infrastructure and intelligent transportation systems have predominantly concentrated on comprehending the transition towards automated mobility. The central question guiding these studies is: How effectively can connected and autonomous vehicles integrate into a sustainable transport future?

Beginning with the assessment of autonomous vehicle impact on physical infrastructure [40], Lv and Zheng [41] pioneered interdisciplinary methods for traffic engineering applications within automated and resilient road systems. Their primary aim was to enhance the resilience of urban road systems by tackling challenges like excessive demand, traffic congestion, and various system failures. In turn, Ghaffarpasand et al. [42] explored the role of telematics in advancing intelligent transportation systems and enhancing road safety. The study emphasized the potential of telematics in supporting emerging urban mobility technologies, specifically at signalized intersections, within vehicle-to-vehicle communication networks, and in various applications within the realms of the Internet of Things and the Internet of Vehicles. Essential for optimizing routing services and reducing road transport fuel consumption by 12–33%, telematics data plays a crucial role in emerging smart city technologies. However, realizing the full potential necessitates continuous efforts in developing effective methods, algorithms, and advanced technologies, such as cloud-based computations, for efficient utilization of telematics data in urban transport.

Georganti et al. [43] investigated the use of Autonomous Vehicles (AVs) on urban interchanges and the design characteristics of road networks to offer seamless, synchronized services for various transportation modes. They addressed global applications of smart payment methods and intelligent transport systems, highlighting the need to overcome implementation challenges. The study analyzed terminals in a tourist-attractive city, evaluating their connection with the urban public transport operator. User surveys and stakeholder interviews revealed approval of public transport automation and multimodality, perceived as resilient, especially during pandemic time. Users also favored interventions improving road infrastructure. The findings align with the evolving urban transport landscape, emphasizing the potential of AVs for interconnecting public transport terminals. The progression of connected and autonomous vehicles promises enhanced travel experiences, improved road safety, and reduced environmental impact. However, advanced mobility applications in diverse traffic environments require a secure, efficient, and resilient communication infrastructure for connected and automated driving systems. Given the growing significance of cooperative driving technologies and their vulnerability to cyber threats, security is crucial. Incorporating Quantum Key Distribution into vehicle-to-infrastructure networks safeguards against quantum computational advances, ensuring secure data communication in urban settings [44]. A similar concern is tackled by [45], focusing on a novel framework for robust autonomous navigation in challenging, unfamiliar environments with mobility-stressing factors like uneven terrain, steep slopes, negative obstacles, and limited visibility due to dust or fog. The system addressed the absence of GPS, degraded perception, and the lack of prior maps, necessitating real-time on-board computation using noisy sensor data. In this context, Stavdas et al. [44] suggested integrating a cryptographic protocol into vehicle-to-infrastructure networks to protect against advancements in quantum computing, thereby ensuring secure data communication in urban settings. However, connected autonomous vehicles represent a significant opportunity for shaping efficient transportation systems.

In this regard, Faghihian et al. [46] conducted a comprehensive survey of energy efficiency methods in connected and automated vehicle technologies. Major findings highlighted that electric-connected and automated vehicles employ distinct approaches, with the control of acceleration and regenerative brakes holding immense potential for efficiency improvement.

Presently, smart cities leverage comprehensive sensor networks for real-time traffic monitoring, collecting significant data. The focus on Connected Infrastructure and Intelligent Transportation Systems is closely tied to the potential benefits of information systems, particularly dynamic speed prediction in traffic sensor networks. Quintana et al. [47] also investigated the effects of reducing traffic speed on the durability of road asphalt layers. Their study revealed a decrease in stiffness and fatigue resistance in the asphalt concrete mixture under repeated loads as traffic speed decreased. Asphalt mixtures from Bogotá, Colombia, showed that reducing speed from 60 km/h to 30 km/h resulted in roughly a 15.6% decrease in asphalt mixture stiffness and a 39.5% reduction in its fatigue life. In turn, Magalhaes et al. [48] delved into forecasting speeds within traffic sensor networks to enhance the decision-making capabilities of traffic management systems. Predicting speeds accurately in urban settings poses challenges due to complex traffic patterns, numerous sensors, and the dynamic nature of sensor networks. However, the installation, replacement, and removal of sensors for maintenance introduce additional complexities.

Moreover, dealing with the dynamic characteristics of real-world sensor networks requires solutions that should be resilient to changes in both traffic patterns and network structures.

Combining insights from these papers allows for a more comprehensive understanding of the role of connected infrastructure in enhancing intelligent transportation systems. The synthesis of findings from eight papers on 'Connected Infrastructure and Intelligent Transportation Systems' highlights the necessity for future research to contribute to the development of appropriate metrics and robust tools for assessing the resilience of roads and intersections. Nevertheless, the absence of traffic sensor networks presents a significant obstacle to providing empirical and dynamic datasets for implementing information systems in road networks and advancing connected infrastructure within the Intelligent Transportation Systems sector.

2.1.3. Dynamic Traffic Management and Adaptive Signal Control

Dynamic traffic management and adaptive signal control play pivotal roles in smart urban initiatives, addressing road and intersection challenges. Research emphasizes real-time data and connected infrastructure to dynamically adjust signal timing, optimizing efficiency. In the broader context of road infrastructure, these studies pursue innovative solutions, underscoring the crucial role of adaptive signal control in establishing responsive and efficient urban transportation systems. However, there is still limited research on how adaptive signal control systems adeptly manage unforeseen traffic conditions or what the repercussions of dynamic traffic management are for intersection efficiency during both peak and off-peak hours.

The pilot study by [49] aimed at modernizing transportation systems through innovative service structures utilizing digital technologies and 5G communication networks. Their digital platform integrated AI algorithms for image recognition, interpreting data from drones or H-D cameras. This allowed real-time updates on Origin–Destination flows, individual trips, and environmental data, disseminating crucial information to citizens. Preliminary findings highlighted the role of dynamic traffic management, including adaptive signal control, in fostering smart mobility applications. The study also underscored the importance of efficient intersection management for overall urban mobility, particularly in disaster–risk scenarios, ensuring swift access to emergency services, and optimizing evacuation routes. Tariverdi et al. [50] underscored the critical role of intersection management in ensuring accessibility to essential services, focusing on healthcare facilities. The study identified areas affected by shocks, underserved populations, and changes in accessibility. This method pinpointed critical road segments, proposing targeted measures to enhance critical public services' resilience. The methodology provided valuable insights for decision-making, revealing real-world impacts like increased access times to health services in Lima due to the 2020 floods.

In this context, the integration of dynamic traffic management with road maintenance strategies has also been investigated [51]. Despite challenges in predicting speeds within extensive and dynamic traffic sensor networks, as explored in [48], the study referred to by [51] examined leveraging big data for informed, intelligent maintenance decisions. The approach targets the enhancement of intersections for durability and efficiency, aiding road maintainers in the initial assessment of road surface conditions. Nevertheless, ongoing research on sustainable and resilient mobility needs to confront challenges in representing extensive road networks, analyzing substantial traffic data, and identifying relevant measures to direct maintainers' attention to crucial data.

Fan et al. [52] introduced an AI-based decision support model enhancing road network resilience for post-hazard recovery. Focusing on intersection management systems, the model aids road network recovery during and after natural disasters, with adaptive signal control playing a crucial role. Despite this, various natural hazards, encompassing geophysical and hydrometeorological events, pose risks to critical infrastructure and technological systems. Meanwhile, Mondal et al. [53] explored the interplay of dynamic traffic management and smart city initiatives, highlighting the significance of intelligent intersection management to improve overall urban functionality. In this perspective, Hettiarachchi et al. [24] reexamined the role of intersection design in promoting sustainable urban stormwater management from a resilience standpoint and explored the potential integration of green infrastructure to mitigate environmental impacts.

Tang et al. [9] introduced a modified metric, drawing inspiration from the "R4" resilience-triangle framework; see also [54]. By incorporating dimensions from resilience engineering and transport science, the authors assessed recurrent congestion based on spatial-temporal traffic patterns in freeway and signal-controlled arterial cases. Results showcased the metric's effectiveness in capturing congestion patterns, offering a quantitative benchmark. While spatial influences on congestion patterns were noted, this resilience-focused metric provided a systemic alternative for congestion assessment, contributing to the toolbox in this domain. However, future work aims to expand the study to a larger scale with diverse traffic scenarios.

Insights from the selected papers on the theme 'Dynamic Traffic Management and Adaptive Signal Control' emphasize the need for future research to integrate road resilience assessment with traffic management. According to [22], a knowledge gap persists in developing assessment tools that guide the selection of intersection types conducive to maintaining stable operation against disruptions and enhancing the overall resilience of road infrastructure.

2.1.4. Urban Mobility Planning and Policy

Five reviewed studies were specifically related to the theme 'Urban Mobility Planning and Policy', and delved into specific aspects of sustainable, resilient, and efficient urban mobility systems.

Docherty [55] viewed connected and autonomous vehicles as a challenging solution for enhancing road safety. However, the widespread adoption of connected and automated technologies presents socio-economic risks, such as increased congestion and urban sprawl. To manage the transition effectively, policymakers should prioritize delivering genuine public value and adopt a cautious approach to prevent undesirable policy path dependencies. Cheek and Chmutina [56], in turn, employed interpretive policy analysis to examine established disaster resilience frameworks, aiming to discern the operational definitions of integrating 'city' and 'resilience'. They concluded that the push for cities to enhance resilience acknowledges the risks associated with globalized urbanization, offering a critique of the current state of urban areas. In this context, the concept of the 15 min city represents a contemporary interpretation of the traditional 'human measure', emphasizing a chrono-centric vision that prioritizes individuals' time, energy, and physio-psychological well-being by minimizing daily commutes [57]. The recent pandemic underscored this potential, demonstrating how the adoption of soft mobility can facilitate outdoor movement and sustained social interactions during lockdowns. In turn, research [58] analyzed the levels of vulnerability and resilience of public transport systems in Rio de Janeiro, Brazil, in the face of threats that can severely affect developing countries. The results showed that areas nearest to the downtown region and those with high-capacity transportation available are more resilient, while a high level of vulnerability is associated with low income, negative socioeconomic indicators, and the predominance of road transportation to reach jobs. In turn, Jindel et al. [59] delved into the study of two-wheeler usage in India within the context of sustainable and resilient urban mobility policies. Despite being a cost-effective transport solution, two-wheelers in India contribute to further externalities such as congestion and road fatalities. The research aimed to enhance existing sustainable policy literature by proposing a new vision to regulate, monitor, and promote sustainable two-wheeler usage. The study also involved reviewing policies, identifying barriers, and proposing reforms to improve policymaking processes and enhance the sustainability of urban transport in Indian cities.

These studies collectively contribute to a comprehensive understanding and improvement of urban mobility planning and policy. However, there is unanimous agreement that it is essential for urban planning to incorporate sustainable road design practices to better align with low-carbon and zero-crash paradigms.

2.1.5. Community Engagement and Behavioral Studies in Urban Mobility

Selected studies on 'Community engagement and behavioral studies in urban mobility' are linked to each other in their shared focus on urban resilience, sustainability, and the impact of external factors like the COVID-19 pandemic [60–66]. They collectively contributed to understanding and improving urban living conditions, exploring concepts such as resilient cities, community viability, transportation needs during pandemics, and the role of infrastructure in fostering prosperity. Also, these studies aimed to inform urban planning and policymaking by considering the behavioral aspects and engagement of communities for more sustainable and resilient urban environments.

In Latin American cities, for example, rampant urban expansion and strategic geographic positioning contributed to vulnerability in the face of natural disasters and human-induced catastrophes. In this context, Cordero and Rodriguez [60] presented a method to detect deficiencies in urban road systems in cities of different sizes. The study utilized various metrics, encompassing topological, geographic, and spatio-temporal indicators, and incorporated network graphs from OpenStreetMap. The results identified susceptible intersections and streets, underscoring the importance of adopting resilient practices and urban management strategies. This is crucial for improving cities' ability to respond effectively to challenges like high population density and mobility in marginalized urban areas. A different examination of impoverished colonias along the U.S.-Mexico border underscored the importance of resilience in the face of challenging circumstances [61]. Despite a lack of infrastructure, residents demonstrate perseverance through familial and communal support networks. The study advocated for recognizing these communities in broader discussions about poverty and called for collaborative efforts to enhance resilience and address housing needs [61]. In this context, further investigation revealed the significant effects of the COVID-19 pandemic on urban mobility, providing insights for the future development of more resilient mobility strategies [62,63]. However, the predominant focus of research has been on scrutinizing the provision of road infrastructure and the impact of technology in strengthening urban resilience [64,65]. Yet, additional investments are crucial for reinforcing resilience, especially in disaster prevention and recovery [66]. The theme highlighted the significance of addressing both the social and environmental aspects of the sustainability framework. It also underscores the promotion of public involvement in decision-making processes to foster more resilient communities.

2.2. Opportunities and Challenges from the Reviewed Papers

This review identified papers primarily focusing on the processes of evaluating resilience in urban road infrastructure at the network or city levels. While recognizing the impossibility of encompassing all tools or approaches, the identified papers mainly concentrate on physical assets in Europe, America, and Asia.

The examined literature has revealed overarching thematic threads and the existence of different approaches to resilience measurements, highlighting barriers and constraints in current assessment methods [30,38]. Limited incorporation of local community-based knowledge across papers restricts the effectiveness of employed approaches, emphasizing the need for a critical appreciation of how urban communities conceptualize their past and future [9,26].

Although boundaries are blurred among the themes, they are distinguishable through the research. The connection between the factors used as search tools and the inquiry about how intersection design or control mode impacts efficiency and resilience at urban intersections mainly aligns with the research domains of 'Resilient Road Infrastructure Design' and 'Connected Infrastructure and Intelligent Transportation Systems' [37].

Resilient road infrastructure design, addressing factors like the physical layout and geometry of roads and intersections, is critical for endurance and recovery from disruptions such as storms [16]. Resilient road designs aim to create durable structures capable of swift recovery both before and after disturbances [66]. The comprehension of how specific intersection shapes may influence efficiency and recovery is a crucial yet unresolved research question [52]. There is a lack of knowledge about design considerations for elevation, road grading, and drainage systems, which influence how effectively an intersection copes with heavy rainfall or flooding. Current approaches are constrained in providing comprehensive representations of resilience metrics and conducting research activities within this context [9]. Connected infrastructure and Intelligent Transportation Systems play a vital role in controlling traffic signals and overall traffic management at intersections [26]. The substantial deployment costs of communication infrastructure may limit widespread implementation, particularly in financially constrained regions [25,29]. Coverage and connectivity issues, especially in remote areas, hinder seamless communication [43]. Vehicle diversity and a lack of educational awareness about real-time communication systems present additional barriers. Successful implementation requires collaborative efforts from technology developers, policymakers, regulatory bodies, and the public.

Furthermore, research should specifically focus on resilience understanding and share the diversity of intersection types supporting vulnerable road users' communities on the road. Also, research should specifically focus on developing specific metrics to measure resilience before and after a disruption. The question regarding the impact of intersection geometry or control mode on efficiency and resilience at urban intersections, particularly, lacks information. In this view, the heuristic approach to assessing the performance efficiency of road intersections in urban environments from a resilience perspective represents a contribution to filling this gap. Also, understanding how people envision their future in the context of resilience assessment is crucial.

3. Materials and Methods

This section outlines the procedural steps taken to start the evaluation of resilience-oriented performance efficiency at urban intersections. A numerical approach is employed to scrutinize traffic patterns across the various conceptualized layouts of urban intersections, facilitating the comparative analysis. Before delving into the details of the proposed methodology, first, the selected urban intersections serving as case studies are identified along with the conducted traffic surveys.

3.1. Case Study Selection and Data Gathering

Four intersections located within neighborhood streets in Palermo City, Italy, have been identified (see Figure 3). To characterize the geometric features of these intersections, on-site inspections were conducted in November 2023 to supplement the information obtained from previous traffic surveys carried out in October and November 2022.

The first case study (referred to as intersection 1) features a compact three-legged roundabout designed in accordance with Italian intersection geometry standards [67]. The roundabout has a 30 m outer diameter one-lane entries and exits, except for the northward entry street, which has two entry lanes (see Figure 3a). The second case study (referred to as intersection 2) involves a three-legged intersection (see Figure 3c), where each street consists of one lane in each direction.

Traffic control for the minor street approach is enforced by a stop sign; raised traffic islands guide turning vehicles and prevent interference with vehicles proceeding straight on the major road. The third case study (referred to as intersection 3) is also a three-legged intersection with one lane in each direction, lacking traffic islands on the streets approaching the intersection (see Figure 3e). Notably, on-site surveys revealed that these lanes present challenges for heavy traffic and public transport due to their narrow road cross-section. The fourth case study (referred to as intersection 4) is a three-legged stop-signed intersection (see Figure 3g), with each street consisting of one lane in each direction. To assess the performance of intersections within the urban road network, traffic data were captured via video recordings during peak hours—specifically, from 7:30 to 9:00 a.m., 12:30 to 2:00 p.m., and 6:30 to 8:00 p.m.—on weekdays from October to November 2022. Traffic counts were conducted at 5 min intervals during morning, noon, and afternoon peaks. Simultaneously, two operators manually tallied traffic data at the same intervals to supplement information on traffic components and turning movements. Case studies 1 to 4 recorded hourly traffic volumes of 1800, 2124, 888, and 1188 vehicles per hour, respectively. Geometric sketches and traffic flows at peak hours for these four case studies are depicted in Figure 3b, Figure 3d, Figure 3f, and Figure 3h, respectively.

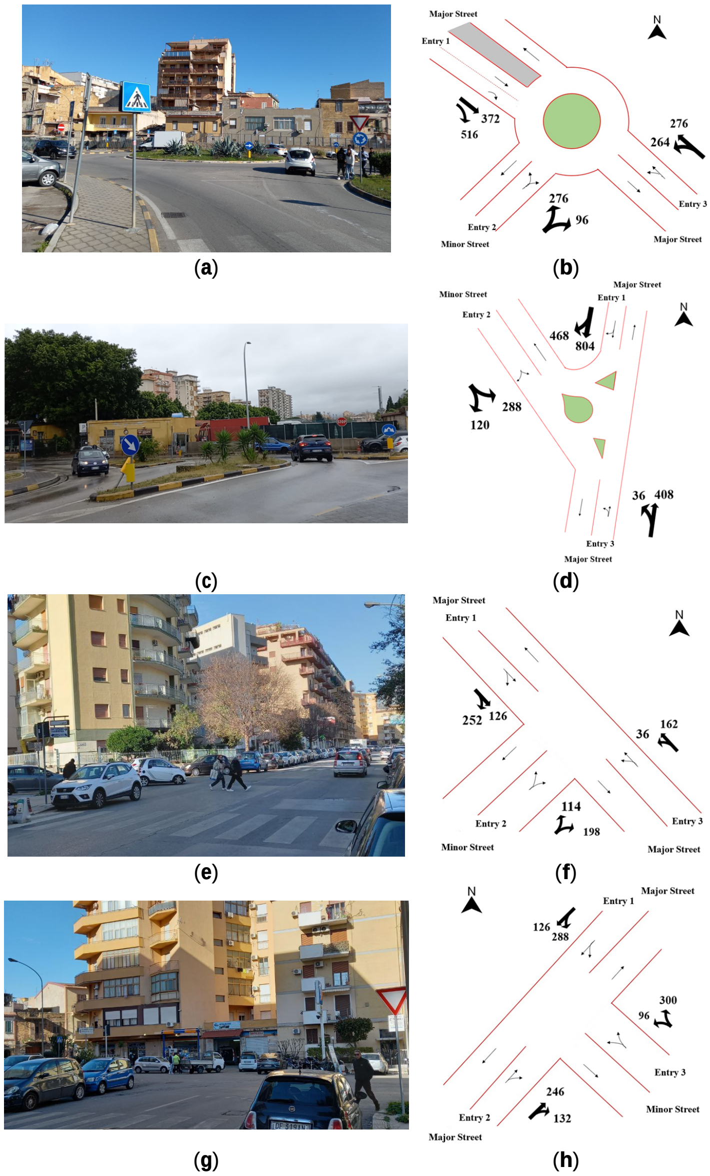

Figure 3. The intersections selected as case studies in the City of Palermo, Italy: (**a**) A view from the southwest entry at intersection 1 (latitude: 38.106082, longitude:13.356868); (**b**) The geometric sketch and the traffic flow of intersection 1; (**c**) A view from the northwest entry at intersection 2 (latitude: 38.102634, longitude: 13.361656); (**d**) The geometric sketch and the traffic flow of intersection 2; (**e**) A view from the southeast entry at intersection 3 (latitude: 38.102203, longitude: 13.355926).; (**f**) The geometric sketch and the traffic flow of intersection 3; (**g**) A view from the southeast entry at intersection 4 (latitude: 38.103412, longitude: 13.354034); (**h**) The geometric sketch and the traffic flow of intersection 4.

According to the traffic data gathered in surveys, intersections 1 and 2 demonstrated greater congestion during peak hours, particularly around noon, compared to intersections

3 and 4. Although factors such as street width, sidewalks, and buildings can be considered potentially pedestrian-friendly, pedestrian volumes were minimal during surveys, so the analysis excluded instances of low pedestrian traffic. This exclusion was attributed to the prevalent use of private cars by residents for their typical commuting between home and work, as indicated by previous research [68]. Table 2 summarizes the geometric details of the examined case studies.

Table 2. The geometric characterization of the intersections selected as case studies.

Intersection	Street Type *	No. Entry (Exit) Lanes	Entry (Exit) Lane Width (m)	Single-Lane Roundabout Width (m)
1	Major	1(1) **	3.50 (5.00)	7.00
	Minor	1(1)	3.50 (3.50)	
2	Major	1(1)	3.50 (3.50)	3.50 ***
	Minor	1(1)	3.50 (3.50)	
3	Major	1(1)	3.50 (3.50)	3.50 ***
	Minor	1(1)	3.50 (3.50)	
4	Major	1(1)	3.50 (3.50)	3.50 ***
	Minor	1(1)	3.50 (3.50)	

* The major and minor streets depicted in Figure 3 are distinguished based on the number of entry lanes, the volume of entry (exit) traffic, or the control mode. ** There are generally one-lane entries and exits, except for the entry from the north direction street, which features two entry lanes. *** The width listed represents the hypothetical roundabout lane dimension for the intersection.

The analysis of intersections in Figure 3 began by taking the size and traffic patterns of each intersection as the baseline scenario. In the pre-storm scenario, each intersection was considered to function either as a roundabout or a signalized intersection. In the post-storm situation, the intersections were assumed to operate as a roundabout or a stop sign intersection. The spatial requirements in the installation area were conducive to conceptualizing each existing type of intersection into alternative forms for assessing and comparing their functional operations in both pre-storm and post-storm scenarios. It is noteworthy that roundabouts generally occupy more space at the intersection area compared to conventional (unsignalized and signalized) intersections within the existing property lines bordered by the built environment [69]. Conversely, conventional intersections typically demand more area on the entry and exit approaches [13,69]. The analysis confirmed the availability of sufficient space within the footprint of conventional intersections where appropriately sized roundabouts could be designed and simulated. Additionally, at the entry and exit points where the current roundabout is installed (i.e., intersection 1), there is enough space to appropriately position other types of intersections for analysis. In alignment with the objectives of the paper, the initial analysis, aimed at testing the feasibility of the proposed methodological approach, focused solely on the average delay time as the index to evaluate the efficiency and resilience of the selected urban intersection types [13,69]. As detailed in the following section, the efficiency of the intersection was explained through a comparison between the roundabout with a signalized intersection before a disruption, while the resilience of the intersection was elucidated by comparing the roundabout with a stop sign intersection after a disruption.

3.2. The Proposed Heuristic Approach

Aligned with the paper's objectives, the analysis considered two distinct scenarios—pre-storm and post-storm—to elucidate and assess the resilience-oriented performance efficiency at the studied intersections situated within neighborhood streets. These scenarios are defined as follows:

1. Pre-storm: this pertains to the normal situation before any storms occur;
2. Post-storm: this situation occurs after the storm has ended, but its impact, such as a lack of electricity, persists.

In the pre-storm scenario, the anticipated types of intersections for operation in the area included a roundabout and a signalized intersection. In contrast, during the post-storm situation, the envisioned types of intersections to function in the area were a roundabout and a stop-sign intersection. Table 3 provides a brief overview of the pre-storm and post-storm situations for the selected intersections.

Table 3. Conceptualization of types of intersection control in pre-storm and post-storm situations.

Situation	Intersection 1	Intersection 2	Intersection 3	Intersection 4
Pre-storm	roundabout signalized intersection	roundabout signalized intersection	roundabout signalized intersection	roundabout signalized intersection
Post-storm	roundabout stop-sign intersection	roundabout stop-sign intersection	roundabout stop-sign intersection	roundabout stop-sign intersection

From this standpoint, the efficiency of the intersection was appraised through a comparison of roundabouts to traffic signals before a disruption, while the resilience of the intersection was assessed by contrasting roundabouts to traffic signals functioning as stop signs after a disruption.

The methodology proposed for evaluating the operational performance of different traffic control types in the examined intersection layouts draws inspiration from the procedures outlined in the Highway Capacity Manual (HCM) [13]. This approach serves as the foundational method for deriving insights into variations in control delay time under both normal conditions and critical events, such as storms. Control delay, commonly understood as the time experienced by users at an intersection due to slower speeds and stops on the approaches, is also influenced by the additional travel time resulting from the operation of a traffic control device. Furthermore, control delay is a key metric used to define the level of service at intersections, representing users' perceived effectiveness [69]. In alignment with the HCM [13], total intersection control delay calculations are typically employed when comparing control delays among different types of traffic controls.

The comparative analysis involved assessing the average delay times for both roundabouts and signalized intersections to evaluate their relative efficiency in normal circumstances. In the aftermath of a storm, certain roads may potentially be obstructed by traffic congestion due to an electricity breakout, leading traffic lights to function as stop signs. The post-disaster scenario envisions a situation where the storm has subsided, but some of its consequences, such as the absence of electricity, persist [19]. Consequently, it is presumed that the signalized intersection would operate similarly to a two-way stop-controlled intersection following the disaster. The evaluation aimed to measure how effectively an intersection could perform in a post-storm scenario concerning changes in delay time values. The performance efficacy of various intersection types during disasters served as an indicator of their resilience. Furthermore, the average delay times of roundabouts and two-way stop-controlled intersections were juxtaposed to assess the resilience of these intersection types in the context of disruptions. Table 4 presents the Formulas (1)–(3) employed for calculating the control delay time in roundabouts, signalized intersections, and two-way stop-controlled intersections, respectively.

The computation of control delay for movements through roundabouts encompasses various components, including the time spent by a driver in decelerating to join a queue, the queue move-up time, the wait time for an appropriate gap in circulating traffic while at the front of the queue, and the subsequent acceleration out of the queue [13]. Equation (1) is employed to measure the average control delay for each lane within a roundabout approach. This equation calculates control delays in a manner analogous to the methods utilized for other unsignalized intersections (refer to Equation (3)). The overall control delay for the entire approach is then determined by computing a weighted average of the delay for each entry lane, with weights assigned based on the traffic volume in each lane. For the calculation of control delay time in signalized intersections, Equation (2) is used, incorporating both uniform and incremental delays for the lane group [13]. It is assumed in this research that the traffic lights operate on a pre-timed basis. Consistent with [13], a study was conducted to compare control delay times between signalized intersections and roundabouts under normal conditions and post-disaster scenarios. This involved computing a weighted average of the delay for each approach, with the weights determined by the traffic volume on each approach, to assess the total intersection delay time.

Table 4. The control delay time calculation formulas.

Type of Control	Control Delay Time (s/veh)	Note
roundabout	$d = \frac{3600}{k} + 900 \cdot t \left[(y-1) + \sqrt{(y-1)^2 + \frac{\left(\frac{3600}{k}\right) \cdot y}{450 \cdot A}} \right] + 5 \cdot \min[y, 1]$	(1)
Signalized intersection	$d = paf \cdot \frac{0.5 \cdot l \cdot \left(1 - \frac{g_e}{l}\right)^2}{1 - \left[\min(1, y) \cdot \frac{g_e}{l}\right]} + 900 \cdot t \left[(y_A - 1) + \sqrt{(y_A - 1)^2 + \frac{8 \cdot j \cdot u \cdot y_A}{C_A \cdot t}} \right]$	(2)
Two-way-stop-controlled intersection	$d = \frac{3600}{c_x} + 900 \cdot t \left[\frac{f_x}{c_x} - 1 + \sqrt{\left(\frac{f_x}{c_x} - 1\right)^2 + \frac{\left(\frac{3600}{c_x}\right) \cdot \left(\frac{f_x}{c_x}\right)}{450 \cdot t}} \right] + 5$	(3)

Note: y is the volume-to-capacity ratio of the subject lane; k is the capacity of the subject lane (veh/h), and it is a function of the entry geometry, circulating roadway width, and the number of circulating lanes; *paf* is the progression adjustment factor; l is the cycle length in seconds; g_e stands for the effective green time in seconds; y_A is the average volume-to-capacity ratio; j is the incremental delay factor; u is the upstream filtering/metering adjustment factor; C_A is the average capacity of vehicles per hour; f_x is the flow rate by movement x; and c_x is the capacity of movement x in vehicles per hour; t is the analysis time period in hours or its fraction.

4. Results

Based on the intersections analyzed in the road network of Palermo, Italy, the efficiency and resilience of case studies 1 to 4 were investigated in both pre- and post-storm scenarios, focusing on average delay times. Figure 4 shows the results of the performance efficiency-based assessment of urban road intersections from the resilience perspective.

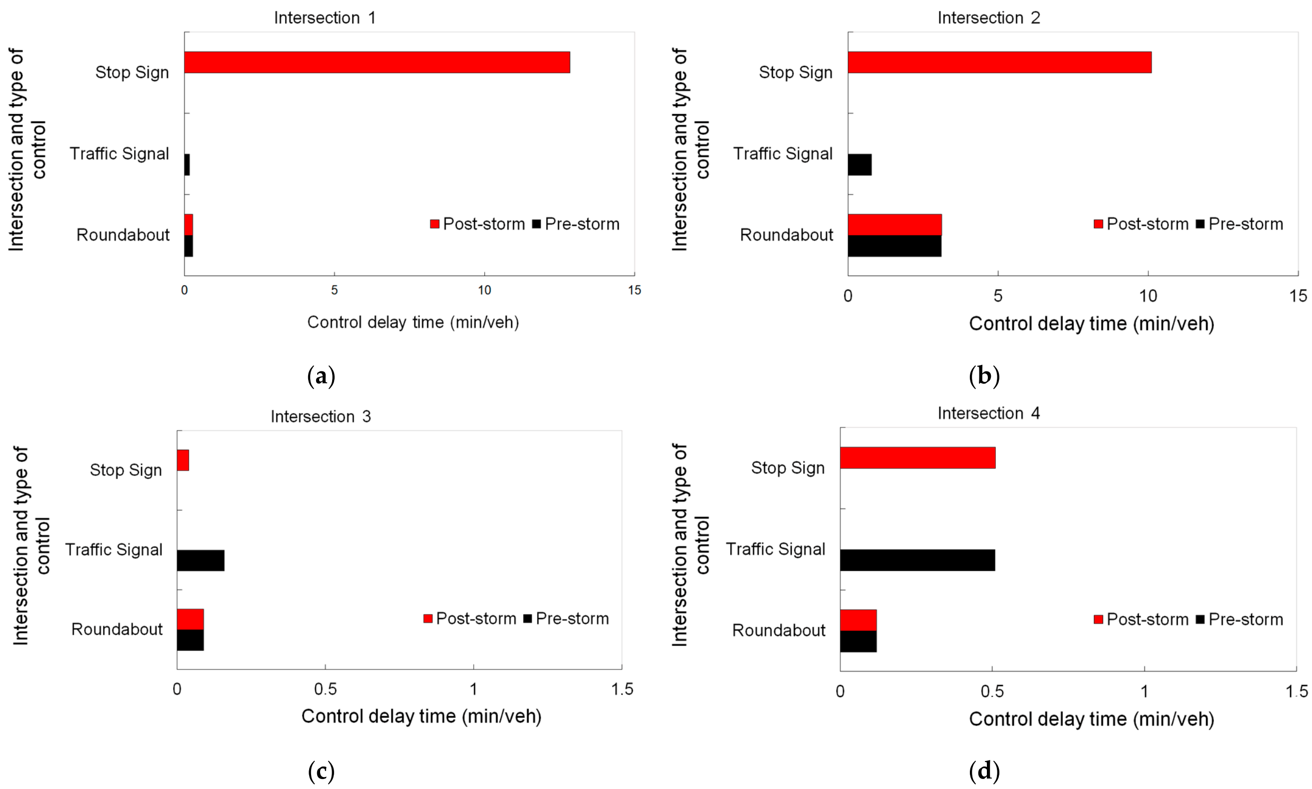

Figure 4. The comparison of efficiency and resilience for the studied intersections in Figure 3, where Traffic Signal and Stop Sign represent signalized intersection and two-way-stop-controlled intersection, respectively: (**a**) intersection 1; (**b**) intersection 2; (**c**) intersection 3; (**d**) intersection 4.

Specifically, Figure 4 showcases clustered bar charts by intersection, comparing roundabouts and signalized intersections. These charts are designed to evaluate the pre-storm relative efficiency of the two types of intersection control. Considering the assumption that, after extreme weather events like storms, signalized intersections operate as two-way-stop-controlled intersections, the average delay times of roundabouts and two-way-stop-controlled intersections were compared to evaluate the resilience of these intersections in the face of disasters. Table 5 presents the control delay values and level-of-service (LOS) determinations by entry approach for case studies 1 to 4 in Figure 3.

Table 5. Pre-storm and post-storm measurements of control delay and level of service by entry.

Intersection	Entry	Pre-Storm (Post-Storm) Roundabout (Roundabout)		Pre-Storm (Post-Storm) Traffic Signal (Stop Sign)	
		Control Delay (min/veh)	LOS [1]	Control Delay (min/veh)	LOS [1]
1	1	0.41 (0.41)	C (C)	0.12 (0.00)	A (A)
	2	0.14 (0.14)	A (A)	0.39 (62.02)	C (F)
	3	0.16 (0.16)	A (A)	0.13 (0.10)	A (A)
2	1	1.01 (1.01)	F (F)	0.90 (0.00)	F (A)
	2	7.03 (7.03)	F (F)	1.19 (52.63)	F (F)
	3	0.53 (0.53)	D (D)	0.10 (0.02)	A (A)
3	1	0.10 (0.10)	A (A)	0.10 (0.00)	A (A)
	2	0.09 (0.09)	A (A)	0.30 (0.11)	C (A)
	3	0.08 (0.08)	A (A)	0.08 (0.01)	A (A)
4	1	0.10 (0.10)	A (A)	0.52 (0.12)	D (A)
	2	0.12 (0.12)	A (A)	0.45 (0.00)	D (A)
	3	0.14 (0.14)	A (A)	0.56 (1.41)	D (F)

[1] LOS means level-of-service, according to [13].

As explained in the previous section, the control delay values in Figure 4 are the total delay times at the selected intersections, calculated as a weighted average of the delay time for each approach, with the traffic volume on each approach serving as the weights.

Intersection 1 (Figure 4a) demonstrated similar control delay times for both roundabouts and signalized intersections in the pre-storm scenario. However, in the post-storm situation where the signalized intersection acted as a stop sign, the roundabout displayed significantly lower control delay times, showcasing its efficiency and resilience.

Intersection 2 (Figure 4b), in pre-storm conditions, found both roundabouts and signalized intersections to be efficient solutions. Post-storm, the roundabout exhibited remarkable resilience, with control delay times more than halved compared to the signalized intersection. Intersection 3 (Figure 4c), with low traffic flow, saw the signalized intersection slightly exceeding the roundabout's control delay under pre-storm conditions. However, the two-way-stop-controlled intersection displayed enhanced resilience post-storm compared to the roundabout. Findings in intersections 1 and 2 indicated reduced resilience of signalized intersections functioning as stop signs after the storm.

The final case study (Figure 4d) illustrated the roundabout layout's resilience after an extreme weather event, emphasizing its ability to maintain functionality irrespective of the event's duration. The study concluded that the choice between roundabouts and signalized intersections should be context-specific, considering factors like traffic conditions, resilience requirements, and associated trade-offs.

5. Discussion

In the pursuit of constructing and maintaining resilient road infrastructure, this study delves into the realm of urban intersection efficiency, guided by the principle of resilience. The findings offer valuable insights into the critical factors for assessing the operational performance of urban intersections in the face of disruptive events, particularly storms (see framework in Figure 1).

The literature review allowed us to contextualize our study within the broader landscape of previous studies and explore the literature gap regarding the integration of performance efficiency and resilience in the assessment of urban road intersections' operations. Thus far, as an early sign consistent with the research topic of this study [70], we have not found similar research in the literature review considering intersection resilience before and after a storm. Additionally, we highlighted avenues for future research to advance our understanding of urban resilience in the context of intersection management.

The study's results in Figure 4 align with the working hypotheses, affirming the robustness of the proposed heuristic methodology, inspired by the Highway Capacity Manual procedure. In the pre-storm scenario, the expected types of intersections for operation in the area were a roundabout and a signalized intersection. In contrast, during the post-storm situation, the envisioned types of intersections to function in the area were a roundabout and a stop-sign intersection (see Table 3).

In intersection 1, the control delay time before a storm is nearly identical for both types of traffic control (i.e., the roundabout and the signalized intersection). Figure 4a indicates that installing a roundabout or a signalized intersection does not significantly affect the intersection's control delay time in a pre-storm situation. However, in a post-storm scenario where the signalized intersection behaves as a stop sign counterpart, the difference between the roundabout and two-way-stop-controlled intersection in terms of control delay time becomes substantial. This result confirms that the existing scheme at the considered site is an efficient and resilient solution. Also, the control delay time values for each approach in intersection 1 (see Table 5) align consistently with the overall intersection result. Consequently, during the pre-storm conditions considered in intersection 2, both the roundabout and signalized intersections were deemed efficient solutions.

However, in the aftermath of the storm, the roundabout exhibited resilience, displaying control delay values that were more than halved compared to the stop sign counterpart (refer to Figure 4b). The control delay time outcomes by approach, detailed in Table 5 for intersection 2, validated the conclusions drawn within the intersection analysis. Overall, a roundabout demonstrates better operational performance compared to a traffic signal in terms of stops, delays, and vehicle queues [69,71]. This assumption holds true during the design phase, provided that the roundabout functions within its intended capacity. However, it is advisable not to apply this assumption in situations where the traffic volume exceeds the designated capacity or unbalanced traffic flows come from the entries [69]. Consequently, roundabouts can result in lower delays than a signalized intersection operating under similar traffic volumes and right-of-way constraints [13]; see Figure 4c,d. Nevertheless, the assessment of whether any roundabout configuration remains effective across various contexts, including situations involving disruptions, prolonged high traffic congestion, or earthquakes, remains an ongoing research question [70–72]. This complexity arises from numerous variables to consider, such as design fees, construction and maintenance costs, as well as factors related to road safety, fuel consumption, emissions, and so on. Alternatively, a signalized intersection can emerge as a feasible choice. However, roundabouts persist as a practical substitute for signalized intersections in cases where intersections are closely positioned, and efficiently handling vehicle queues between successive intersections presents difficulties. Hence, it is crucial to assess the conditions specific to the site before selecting the suitable intersection type, as each option involves unique considerations and trade-offs [73,74].

Examining Figure 4c, the total control delay in the signalized intersection, as demonstrated in intersection 3 under pre-storm conditions, slightly exceeds the values in the roundabout counterpart used for comparison purposes. This outcome was expected due to the low traffic flow and density observed in the field. Conversely, the decreased delay at the two-way-stop-controlled intersection in the post-storm situation signifies the enhanced resilience of that intersection design compared to the roundabout. The control delay times for each approach align with these findings (refer to Table 5). In contrast to intersection 3, in intersections 1 and 2, the elevated delay at the traffic signal functioning as a stop sign intersection after the storm indicated the diminished resilience of these intersection configurations in comparison to the roundabout alternative [69]. Regarding the latest case study in Figure 4d, the clustered bar charts display the resilience of the roundabout layout, which was conceptualized for comparison purposes. In other words, they showcase the resilient response capability of the roundabout design after the imagined extreme weather event used to illustrate the proposed methodological approach. Thus, the roundabout system is designed to maintain functionality irrespective of the event's duration.

From a broader context, our findings emphasize the pivotal role of intersection design and control strategies in shaping urban resilience. This contributes to outlining valuable perspectives for road infrastructure design and management, advocating for a paradigm shift towards adaptable designs that prioritize resilience. The research has practical implications for urban planning and transportation engineering. The study highlights the adaptability and resilience of roundabouts, suggesting a potential shift in design preferences, particularly in regions prone to disruptive weather events. This has tangible implications for policymakers and engineers managing intersections in an unpredictable climate.

While acknowledging some gaps in the HCM procedures [13], as referenced in the literature [75,76], the analytical approach outlined by the HCM emerged as the most appropriate for presenting the innovative heuristic that combines efficiency and resilience in the performance evaluation of urban intersections. At this phase of the study, the performance of each isolated intersection is overall compared before and after a storm, focusing solely on delay times. The Highway Capacity Manual [13] is recognized for documenting all delays resulting from a specific bottleneck, regardless of where vehicles are physically located. In contrast, simulation models only report delays on the street segment where vehicles are decelerating. Additionally, these models may not always account for control delays at signalized intersections. The reported values typically encompass midblock delays for vehicles traveling along the link or solely the delay incurred when vehicles come to a stop at traffic signals [75]. From this viewpoint, it was not possible to employ any microscopic traffic simulation model to compare delays before and after a storm across the different conceptualized intersections. Moreover, there are differences not only in the methodological approaches between simulation models and the HCM tool but also in the definitions of the performance measures they provide. These differences induced us to use the HCM tool [13,75]. However, the next research step of the study will necessarily include a comparative analysis of different intersection types in a microsimulation environment to evaluate the dynamic evolution of traffic congestion problems at intersections [77]. In this perspective, a comparison among different microsimulation software could be performed to better select the most appropriate tool based on the intersection type and level of saturation within the simulation case [76,78].

Looking ahead, our study suggests several avenues for future research. A more in-depth exploration of specific design attributes contributing to intersection design resilience could provide actionable insights for urban planners. The study notes fluctuations in delay times for traffic signals both before and after a storm, emphasizing the need for site-specific analysis considering size, traffic patterns, and network position. The integration of emerging technologies, like intelligent traffic management systems, could enhance urban intersection resilience. Exploring the socio-economic implications of resilient intersection designs and their role in community resilience presents another promising avenue. In conclusion, this study significantly contributes to the discourse on urban resilience, emphasizing intersection efficiency. The alignment of results with hypotheses, implications for urban planning, and identification of future research directions position our findings as a scientific and societal contribution. Embedding resilience into intersection design and assessment is crucial for sustainable and adaptive transportation infrastructure amid evolving climate and urban landscapes.

6. Conclusions

The paper introduces a novel heuristic approach to assess the operational efficiency of urban road intersections from a resilience perspective. The review of literature established the research's significance, addressing opportunities and challenges in new road infrastructure development within a transitioning context. Specifically, the study emphasizes the necessity for an adaptable evaluation methodology, drawing insights from existing literature in which the absence of specific and universally accepted metrics for assessing resilience in the operational performance of road infrastructure represents the gap that the paper aims to contribute to filling.

Using case studies in Palermo, Italy, the research focused on pre- and post-storm scenarios, assuming intersections function as roundabouts or signalized/stop-sign intersections. Consequently, the efficiency of the intersections was analyzed by comparing roundabouts to traffic signals before a storm, while their resilience was assessed by comparing roundabouts to stop signs after a storm. The evaluation of delay times at roundabouts and signalized intersections before and after a storm aligns with our hypothesis that disruption-resistant designs and control strategies can enhance urban intersection efficiency. Notable changes in traffic signal delay times underscored the vulnerability of conventional intersection designs to disruptions and validated the need for a resilience-centric approach. By shedding light on the interplay between intersection design, control strategies, and urban resilience, this research provides valuable insights into integrating resilience considerations into intersection performance assessment and management strategies. It also underscores how particular intersection designs can impact efficiency and recovery, essential considerations when assessing whether a road or intersection project is resilient.

Furthermore, the paper advocates for the inclusion of the resilient perspective in intersection performance assessments over the lifespan. Recognizing the increasing demand for road systems characterized by adaptability, automation, and resilience, this study provides a scientific contribution by guiding the selection of intersection types to guarantee stability amid disruptions, be they natural or human-induced. From a societal perspective, the research further underscores the necessity for approaches that facilitate the exchange of information among road users and operators, aiming to foster coordinated actions within more advanced driving systems.

Acknowledging gaps in HCM procedures [75,76], its analytical approach was vital for presenting a heuristic blending efficiency and resilience in urban intersection performance assessment. Consistent with the objectives of the paper, this initial analysis allowed us to test the feasibility of the methodological approach we proposed, focusing solely on the average delay time to evaluate the performance efficiency of the selected intersections before and after storms with resilience as its guiding principle.

Recognizing limitations and reliance on assumptions, future advancements might entail automated estimation of intersection delays using turning movement data and computational procedures for queue-related measures. Further, future developments will inherently also involve the assessment of the dynamic evolution of traffic problems at intersections by using microsimulation. From this standpoint, it would be preferable to compare different microsimulation software to better select the most appropriate tool based on the intersection type and level of saturation within the simulation case. Additionally, analyzing operations at a small network level is anticipated, with consideration of geometric delays in systems analysis, particularly in smart intersections, in the near future.

Author Contributions: Conceptualization, N.Z., E.M., A.G. and T.G.; methodology, N.Z., E.M., A.G. and T.G.; software, N.Z.; validation, N.Z.; formal analysis, N.Z., E.M., A.G. and T.G.; investigation, N.Z., E.M., A.G. and T.G.; resources, E.M., A.G. and T.G.; data curation, N.Z.; writing—original draft preparation, N.Z., E.M., A.G. and T.G.; writing—review and editing, N.Z., E.M., A.G. and T.G.; visualization, N.Z., E.M., A.G. and T.G.; supervision, E.M., A.G. and T.G.; project administration, E.M., A.G. and T.G.; funding acquisition, E.M., A.G. and T.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be provided upon kind request to the corresponding authors.

Acknowledgments: Sustainable Mobility Center (Centro Nazionale per la Mobilità Sostenibile—CNMS) under Grant CN00000023 CUP B73C22000760001. This publication is supported by the Rector's Pro-Quality Grant, Silesian University of Technology, Poland, grant number 12/040/RGJ24/0064, and Silesian University of Technology grant number BK-285/RT4/2024, 12/040/BK_24/0065.

Conflicts of Interest: The authors declare no conflict of interest.

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