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Olympic Mobility: Assessing the Impact of Transit Flows During the Milano Cortina 2026 Winter Olympics

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Abstract

The Milano Cortina 2026 Winter Olympic Games represent a significant departure from traditional mega-event models due to their markedly polycentric territorial structure. This study investigates the sustainability of this "decentralized" model by analyzing the environmental impact of mobility flows across a vast geographic area. Adopting a methodological approach, the research integrates historical attendance data from previous Winter Games with official projections and travel time simulations to model the event's carbon footprint. Specifically, the framework quantifies gas emissions by categorizing mobility flows into external international travel and internal inter-cluster transit. The analysis highlights a significant discrepancy between the stated sustainability objectives and the actual implementation of the infrastructural plan. Findings reveal that the total carbon debt is heavily driven by international travel, yet the localized impact on Alpine clusters remains critical due to a persistent reliance on road infrastructure over rail systems. The results suggest a "paradox of decentralized sustainability", where the benefits of reusing existing sporting venues are offset by the environmental costs of connecting geographically fragmented sites. We conclude that without a robust and efficient public transport network, territorial dispersion acts as a catalyst for widespread anthropogenic pressure on fragile mountain ecosystems, challenging the long-term ecological legacy of the event. By empirically exposing these dynamics, this study offers a novel evaluative framework for assessing the true sustainability of distributed governance in future mega-events.

Keywords: Milano Cortina 2026; Winter Olympics; sustainable mobility; carbon footprint; mega-event logistics; alpine ecosystems; decentralized mega-events

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1. Introduction

Mega-events represent one of the most intensive and visible forms of tourism-driven territorial transformation, generating short-term concentrations of visitors, infrastructure demand, and mobility flows at multiple spatial scales (Barbu, 2025; Cerezo-Esteve et al., 2022; Garay et al., 2014; Jago et al., 2010; Lauermann, 2019; Martins et al., 2025; Ripp et al., 2025). Within this category, the Olympic Games stand as the most complex and pervasive phenomenon, capable of shifting global attention and mobilizing a massive, heterogeneous network of athletes, media, corporate stakeholders, and international spectators. Recent editions of the Winter Olympic Games have involved more than one million spectators and workforce participants, hundreds of thousands of tourists, thousands of athletes and media personnel, and global television audiences measured in billions (Davico, 2006; International Olympic Committee, 2024b). This unprecedented influx exerts an immediate, systemic pressure on the hosting region, effectively reshaping local carrying capacities and creating a temporary macro-system within the existing urban and regional fabric. Among the various dimensions of sustainability associated with large-scale sporting events (Kietlinski, 2021; May, 1995; Prudnikova, 2012; Scott et al., 2015; Song et al., 2018; Vanwynsberghe, 2014), mobility has consistently emerged as a primary driver of environmental impact, particularly in terms of greenhouse gas emissions linked to spectator, workforce, and logistics-related travel (Bae & McCullough, 2025; Ballarano et al., 2022). Unlike fixed infrastructures or venue-related emissions, mobility-related impacts extend far beyond event boundaries, involving national and international transport systems and shaping the overall carbon footprint of the event.

Following Müller (2015), mega-events are not defined solely by their sporting dimension but by a combination of visitor attractiveness, costs, mediated reach and transformative impact. Within this framework, the Olympic Games (both summer and winter) qualify as mega-events primarily due to their exceptional capacity to attract large volumes of visitors beyond local demand.

In this context, carbon footprint assessment has become a key analytical tool for evaluating the environmental sustainability of tourism mega-events (Su et al., 2025). By translating complex mobility patterns into comparable emission metrics, carbon accounting allows researchers and policymakers to identify critical sources of impact, compare alternative planning scenarios, and assess the coherence between sustainability objectives and actual mobility outcomes (Bae & McCullough, 2025). Previous studies have shown that transport-related emissions often account for the largest share of the total footprint of major sporting events, particularly when long-distance travel and fragmented spatial configurations are involved (Dosumu et al., 2014; Simmonds & Pielke, 2024; Tóffano Pereira et al., 2019).

In the broader context of sport tourism scholarship, carbon footprinting is increasingly recognized not just as a static measurement, but as a critical diagnostic component within sustainable event management frameworks and long-term legacy planning (Mair & Smith, 2021; Preuss, 2007). Scholars in sport management emphasize that the environmental legacy of a mega-event is heavily dependent on the governance approaches and transport planning strategies established during the bidding and preparation phases. When an event adopts a polycentric or decentralized model, transport planning ceases to be a temporary logistical operation and becomes instead a core determinant of the regional mobility legacy. Consequently, integrating carbon accounting into sport tourism research allows for a more robust evaluation of whether the governance goals of “green” or “carbon-neutral” Games align with actual structural outcomes (Gaffney, 2013), thereby contributing to the theoretical understanding of how sport-induced tourism shapes sustainable territorial development.

The environmental relevance of mobility is further amplified in mountain and alpine tourism contexts, where geographical constraints, limited transport infrastructure, and high ecosystem sensitivity interact to intensify the impacts of visitor flows. Alpine regions are characterized by reduced resilience to anthropogenic pressure, constrained modal alternatives to road transport (Senese et al., 2025c; Senese et al., 2023), and elevated emission intensity per trip due to distance, topography, and climatic conditions (Senese et al., 2025a; Steiger et al., 2024). In such settings, even moderate increases in mobility demand can generate disproportionate environmental effects, challenging conventional assumptions about the sustainability of tourism development in fragile territories (Mouhou, 2025).

These dynamics are particularly relevant for mega-events adopting decentralized territorial models, in which competition venues and tourist destinations are spatially dispersed across wide regions (Parncutt et al., 2019). While decentralization is often presented as a strategy to limit land consumption through the reuse of existing facilities

(Dolasinski & Roberts, 2025; Perechuda, 2025), it may simultaneously increase mobility requirements and associated emissions, especially in the absence of efficient intermodal transport systems. Theoretical and empirical studies in transport geography suggest that polycentric spatial configurations increase the complexity of mobility systems by dispersing activity centers, expanding travel interactions between nodes, and generating more heterogeneous origin–destination patterns (Burger & Meijers, 2012; Veneri, 2010). Consequently, evaluating mobility-related sustainability in such systems requires shifting from a simple volume-based calculation to a spatial-efficiency analysis. This assessment must evaluate whether the emissions saved by avoiding new venue construction are offset by the carbon penalties generated by increased inter-urban and valley-to-valley transit, which typically relies more heavily on private and road-based transport due to the lower viability of continuous rail infrastructure in complex topographies. This potential trade-off highlights the need for integrated assessments that explicitly account for mobility-related impacts when evaluating the sustainability of polycentric event models.

The 2026 Milano Cortina Winter Olympic Games represent an unprecedented case study in this respect (Gaudette et al., 2017). Characterized by a markedly polycentric configuration spanning more than 22,000 km^2 across urban centers and alpine destinations (International Olympic Committee, 2025), the Games provide a unique opportunity to investigate how mobility flows shape the carbon footprint of a large-scale tourism event in a mountain context. Within this context, the present study aims to assess the environmental impact of mobility associated with Milano Cortina 2026 by estimating the carbon footprint of transport flows. Specifically, the present study addresses the following research questions: to what extent does the decentralized territorial structure of the Milano Cortina Games influence mobility-related carbon emissions, and how are these emissions distributed across different spatial scales and transport modes? While scholarship on mega-event sustainability has expanded considerably over the last two decades, particularly with regard to environmental impacts, carbon emissions, and event legacy assessment (Bae & McCullough, 2025; Caccialanza et al., 2024; Cerezo-Esteve et al., 2022), most transport-related sustainability analyses remain grounded in centralized host-city models (Fabre et al., 2026; Lopes Dos Santos et al., 2022). As a result, the spatial dynamics and environmental trade-offs associated with large-scale polycentric configurations in fragile mountain ecosystems remain comparatively underexplored. This study addresses this gap by offering three distinct contributions. First, it introduces a novel methodological framework that couples historical attendance modeling with localized travel-time simulations across multi-regional scales. Second, it shifts the analytical focus from a static, volume-based emission count to a spatial-efficiency analysis, empirically testing the "paradox of decentralized sustainability". Finally, it provides a replicable diagnostic tool for future event planners to evaluate whether the carbon savings achieved through venue reuse are offset by the transport penalties of territorial dispersion.

2. Study Area and Event Context

The Milano Cortina 2026 Winter Olympic Games are characterized by a highly fragmented territorial configuration, extending from major metropolitan areas to remote Alpine valleys across Northern Italy. Competition venues are distributed among several distinct clusters, including the Milan metropolitan area, Cortina d'Ampezzo, Valtellina (Bormio and Livigno), Val di Fiemme, and Antholz (Anterselva), spanning more than 22,000 km^2 across two Regions and two Autonomous Provinces (Figure 1). This polycentric spatial arrangement represents a significant departure from the traditional, compact Olympic model and constitutes a defining feature of the Milano Cortina event system (Gaudette et al., 2017).

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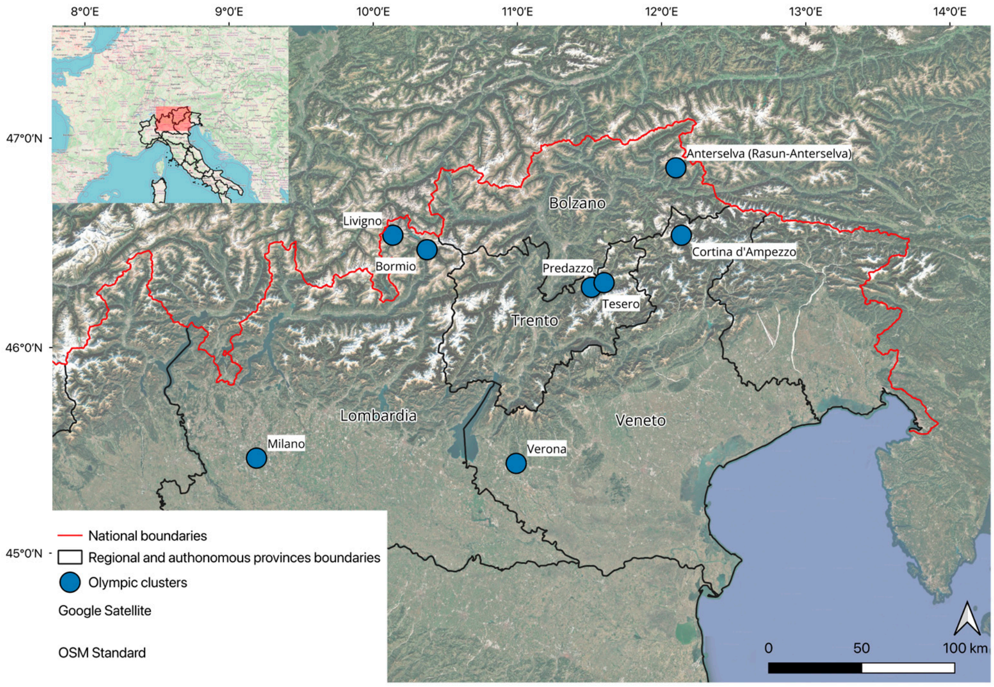

Figure 1. Location map of Milano Cortina 2026 Winter Olympic Games with all the distributed clusters.

From a governance and planning perspective, the decentralized structure of the Games has been presented as an opportunity to reduce land consumption through the reuse of existing sporting facilities and to distribute economic benefits across multiple tourism destinations (International Olympic Committee, 2018). In the context of regional planning, this decentralized configuration operates as a multi-hub network model, where primary metropolitan gateways (such as Milan) serve as logistical and transit anchors connected to highly specialized, geographically isolated peripheral nodes (the Alpine clusters) located up to several hundred kilometers away (Lopes Dos Santos et al., 2022). At the same time, however, such territorial dispersion inherently increases the complexity of mobility management, requiring efficient intermodal connections to ensure accessibility for spectators, athletes, staff, and media. In this context, mobility emerges as a critical interface between territorial organization, tourism dynamics, and environmental sustainability.

Intermodal accessibility to, from, and between the various Olympic clusters therefore represents a pivotal element for assessing the sustainability of the event. The spatial fragmentation of venues (ranging from the Milanese urban system to high-altitude alpine locations) implies long travel distances and multiple modal transfers, particularly for visitors relying on public transport (Lopes Dos Santos et al., 2022). Travel time simulations and accessibility assessments indicate that connections between major gateways and mountain venues remain time-intensive and operationally complex, with public transport journeys often exceeding those by private car by several hours (Lopes Dos Santos et al., 2022). Such conditions tend to discourage a modal shift toward collective transport solutions and incentivize reliance on individual road-based mobility.

3. Materials and Methods

This study adopts a quantitative modeling approach based on secondary data integration and scenario simulations to assess greenhouse gas emissions from tourism-related mobility flows. This integrated modeling technique follows established frameworks in sustainable event management and sport tourism research, where secondary data syntheses and spatial simulations are coupled to reconstruct visitor transport demand in data-scarce environments (Dietl & Frick, 2007; Smallwood et al., 2011). The methodological frame-

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work relies on the synthesis of historical attendance records, official event sustainability benchmarks, and spatial navigation data to simulate transport patterns associated with the Milano Cortina 2026 Winter Olympic and Paralympic Games. Specifically, mobility flows are categorized into external and internal components, in order to distinguish between different spatial scales of transport demand. External mobility refers to all travel flows occurring between the place of origin of spectators and the Olympic macro-region, including both international and domestic trips required to reach the event area. Internal mobility, by contrast, refers to movements within the Olympic system, specifically between the different competition clusters and host locations during the event period. These flows are primarily associated with spectator attendance at multiple venues, as well as logistical movements across the polycentric territorial structure of the Games.

3.1. Estimated Attendance for the Olympic Event (External Flows)

External flows represent all travel movements connecting the place of origin of visitors with the Olympic macro-region, including both international and domestic arrivals. Their estimation was based on a multi-step approach integrating historical data, benchmark event models, and contemporary travel indicators.

First, attendance figures from previous Winter Olympic Games (1980–2018) were analyzed to establish a statistical baseline for the expected number of spectators and workforce associated with the event. These historical data were used to validate the plausibility of the official projection for Milano Cortina 2026 (International Olympic Committee, 2024b).

In addition to accredited spectators and workforce, the total attendance estimate includes a share of non-ticketed visitors attracted by the event. These visitors comprise individuals attending public fan zones, tourists visiting host destinations during the Olympic period without accessing competition venues and accompanying travelers. This component was incorporated to account for the broader tourism effect generated by the Games and its contribution to overall mobility demand. The inclusion of non-ticketed visitors is coherent with definitions of mega-events that emphasize visitor attractiveness as a core dimension, referring to the ability of such events to draw large temporary populations independently of formal attendance metrics (Müller, 2015). Empirically, the volume of approximately 450,000 non-ticketed visitors was derived through a top-down residual calculation based on the verified target of 2.0 million total visitors expected within the macro-region (Bianchi, 2025). By subtracting the official baseline of approximately 1.55 million primary ticketed spectators and accredited workforce from this total macro-figure, the remaining share of around 450,000 individuals was allocated to non-ticketed flows. This residual component accounts for the broader tourism leverage effect, encompassing event-induced regional tourists, participants in public fan zones, and accompanying travelers (Ritchie & Adair, 2004; Weed, 2012). To ensure physical and logistical plausibility, this extracted volume was cross-referenced with, and validated against, the regional hospitality infrastructure. The 450,000 figure strictly respects the maximum threshold of unaccredited daily arrivals that can be dynamically absorbed by the commercial bed capacity and secondary housing markets of the involved territories without oversaturating the regional accommodation supply.

Second, the geographical distribution of visitors was derived from the Paris 2024 Sustainability Report (International Olympic Committee, 2024a), which provides a detailed breakdown of spectator origins across different spatial categories (domestic, European, and international long-haul markets). This dataset was adopted as a reference model for the structure of external flows and subsequently adjusted to reflect the specific characteristics of a winter sports event. In particular, weighting coefficients were applied to account for the higher relevance of European markets and the reduced share of long-haul visitors typically associated with Winter Olympic Games. This approach assumes that while the overall structure of spectator provenance is transferable, its relative weights must be adapted to account for the specific demand patterns of winter sports tourism. The adoption of the Paris 2024 dataset as a baseline does not imply a direct behavioral equivalence between the two events; rather, it provides a standardized, IOC-validated methodological framework for categorizing visitor provenance scales. To resolve the structural divergence between a highly centralized, rail-dominated metropolitan summer event and a fragmented, alpine winter event, specific scaling factors were applied. First, the share of long-haul international visitors was statistically downscaled, reflecting historical winter sports demand which is traditionally dominated by domestic and alpine-adjacent European markets. Second, while the baseline model anchors transport mode to origin distance, the modal split was systematically re-calibrated by applying a road-transport penalty coefficient to the internal routing. This mathematical adjustment accounts for the steep topographies, lower high-speed rail density, and winter climatic variables characteristic of the Lombardy and Veneto alpine valleys, effectively converting high-capacity rail shares into increased private vehicle and collective shuttle coach shares (Godovykh, 2024; Le et al., 2019).

Third, these distributions were further refined using contemporary travel indicators, including aggregated air travel and transaction data (Gentili et al., 2025), which provide quantitative evidence of increasing international demand for travel to Italy during the Olympic period and help to validate the geographical distribution of external flows.

In addition to the geographical distribution of visitors, the modal split associated with external mobility was derived from the Paris 2024 Sustainability Report, which provides a detailed breakdown of transport modes by region of origin. Also in this case, this dataset was used as a reference framework to model the relationship between travel distance and transport choice. The Paris 2024 modal distribution was not directly transferred but adapted to reflect the specific characteristics of the Milano Cortina 2026 Winter Games. In particular, adjustments were applied to account for the alpine context, the reduced accessibility of mountain destinations, and the lower availability of high-capacity rail connections compared to a metropolitan setting such as Paris. As a result, the modal split was calibrated by maintaining the structural relationship between distance and transport mode (e.g., increasing reliance on air travel for long-haul flows), while modifying the relative shares of car, rail, and collective transport to better represent the expected mobility behavior of spectators traveling to dispersed alpine venues.

The resulting model enabled the estimation of external mobility flows by integrating total attendance figures with a geographically segmented distribution of spectators and a calibrated modal split by region of origin.

3.2. Estimation of Internal Flows

Internal mobility flows refer to all movements occurring within the Olympic macro-region, specifically between the different competition clusters and host locations during the event period. These flows are primarily associated with spectators attending events across multiple venues within a decentralized territorial system. In particular, not all visitors were assumed to generate inter-cluster mobility. Internal flows were modeled considering only the subset of visitors likely to attend events across multiple locations or to travel between clusters.

The estimation of internal flows was based on a multi-step approach integrating attendance distribution, event allocation, and spatial accessibility considerations. The spatial distribution of the estimated total attendance across Olympic clusters was derived using a proportional allocation framework based on three main variables.

First, the total number of visitors was distributed across the Olympic clusters according to their hosting capacity. This allocation was informed by a comparative analysis of previous Winter Olympic Games and adjusted based on the number of events assigned to each venue and their maximum seating capacity, which defines the upper bound of accredited spectators (Table 1).

Table 1. List of venues for Milano Cortina Olympic Games (Italian National Olympic Committee, 2026).

City	Venue	Maximum Seating Capacity	Sport	Number of Days of Use
Milano	Arena Santa Giulia	16,000	Ice Hockey	18
Milano	Meazza Stadium	76,000	Opening Ceremony	1
Verona	Arena	15,000	Closing Ceremony	1
Cortina d'Ampezzo	Cortina Sliding Centre	5500	Bobsleigh; Skeleton; Luge	14
Cortina d'Ampezzo	Tofane Alpine Skiing Centre	7000	Alpine Skiing	8
Cortina d'Ampezzo	Cortina Curling Olympic Stadium	3000	Curling	19
Milano (Assago)	Milano Ice Skating Arena	9700	Figure Skating; Short Track	16
Bormio	Stelvio Ski Centre	7000	Alpine Skiing; Ski Mountaineering	10
Livigno	Livigno Snow Park	10,400	Freestyle Skiing; Snowboard	14
Livigno	Livigno Aerials and Moguls Park	3000	Freestyle Skiing	10
Predazzo	Predazzo Ski Jumping Stadium	5000	Nordic Combined; Ski Jumping	9
Rasun-Anterselva	Anterselva Biathlon Arena	19,000	Biathlon	10
Milano (Rho)	Milano Ice Park	13,300	Ice Hockey; Speed Skating	18
Tesero	Tesero Cross-Country Skiing Stadium	15,000	Nordic Combined; Cross-Country Skiing	13

Second, this initial distribution was refined by incorporating factors influencing spatial attractiveness. These include the type and popularity of sporting disciplines, the presence of Olympic Villages and major logistical hubs, and the overall tourism appeal of host destinations. These elements were used to adjust the relative weight of each cluster within the total distribution of visitors.

Third, accommodation capacity, expressed in terms of available lodging facilities and beds, was incorporated to reflect the ability of each cluster to host both ticketed spectators and non-ticketed visitors. This variable also constrains the maximum number of visitors that can be accommodated in alpine areas.

Internal mobility flows between clusters were then estimated by modeling potential travel demand generated by spectators attending events in multiple locations. This approach assumes that a share of visitors is likely to be accommodated in primary hubs (e.g., Milan and Verona) and to travel to peripheral venues for specific competitions, generating inter-cluster mobility patterns consistent with the spatial organization of the event.

This approach also allowed for a differentiated allocation of non-ticketed visitors. A higher proportion of these visitors was assigned to the Milan metropolitan cluster, where large-scale fan zones and urban attractions are expected to concentrate event-induced tourism. In contrast, the share of non-ticketed visitors in alpine clusters was constrained by logistical limitations and accommodation capacity in mountain valleys.

The final distribution of visitors by location was used as the baseline for estimating internal mobility demand and associated emissions. Crucially, these deterministic allocations represent a structured, scenario-based simulation of potential macro-flows rather than a precise predictive forecast of individual behavioral choices (Gospodini, 2001). Given the inherent volatility of multi-destination tourism choices, weather-dependent alpine transit, and real-world modal shifts, the resulting emission estimates contain structural uncertainties. Consequently, the quantitative outputs must be interpreted with caution as deterministic indicators of systemic pressure scales rather than absolute empirical values. This spatial and behavioral variability is precisely why these baseline values are subjected to rigorous multi-parameter perturbation in the subsequent sensitivity analysis, which establishes the operational confidence intervals of the carbon footprint.

3.3. Carbon Footprint Calculations

The environmental impact of mobility was quantified using a carbon footprint ($CO_{2\text{-eq}}$) assessment framework. Emission factors and calculation procedures were derived from established methodologies described in Caserini et al. (2019), Senese et al. (2025a), Senese et al. (2025b) and Senese et al. (2024). Total mobility-related emissions ($E_{mobility}$, kg $CO_{2\text{-eq}}$) were calculated as the product of the number of passengers (N), the average distance traveled (D, km), and the emission factor associated with each transport mode (EF, Table 2), according to the following formula:

$$E_{mobility} = N \times D \times EF \quad (1)$$

Table 2. List of all emission factors considered in this study and the relative source.

Vehicle	Emission Factor	Source
Car	0.111 kg $CO_{2\text{-eq}}$/km/pass	Adapted from Senese et al. (2024)
Train	0.033 kg $CO_{2\text{-eq}}$/km/pass	Senese et al. (2024)
Bus	0.014 kg $CO_{2\text{-eq}}$/km/pass	Senese et al. (2024)
Plane (<1500 km)	0.123 kg $CO_{2\text{-eq}}$/km/pass	Caserini et al. (2019)
Plane (1500–4000 km)	0.093 kg $CO_{2\text{-eq}}$/km/pass	Caserini et al. (2019)
Plane (>4000 km)	0.052 kg $CO_{2\text{-eq}}$/km/pass	Caserini et al. (2019)

The average distance traveled was estimated differently for external and internal mobility flows. For external mobility, distances were defined as average round-trip values based on the geographical origin of visitors. Three main categories were considered: Italy and neighboring countries (average distance: 600 km), medium-distance European markets (2000 km), and long-haul international travel (14,000 km). These values were derived from typical travel distances between origin regions and the Olympic macro-region and were used as representative averages for each category.

For internal mobility, distances were estimated using geolocation and navigation application programming interfaces (Google Maps ©2026), based on the main transport corridors connecting Olympic clusters. Simulated travel routes were used to approximate realistic inter-cluster distances under typical traffic and accessibility conditions. These values were applied to model mobility flows between primary hubs (e.g., Milan and Verona) and peripheral alpine venues.

All emission factors are expressed in kg $CO_{2\text{-eq}}$ per passenger-kilometer and refer to average Italian operational conditions, as specified in the cited sources. For private road transport, an Italian baseline emission factor of 0.166 kg $CO_{2\text{-eq}}$ km^{-1} per vehicle was adopted, reflecting the average characteristics of the national vehicle fleet (Caserini et al., 2019). This value was converted into a passenger-based emission factor by applying an average vehicle occupancy rate representative of the Italian context. While the reference occupancy rate reported in the literature is 1.3 passengers per car (Senese et al., 2024), this parameter was adjusted to 1.5 passengers to reflect the social and logistical characteristics of mega-events, where shared travel is more frequent. On this basis, the resulting emission factor for private mobility was set at 0.111 kg $CO_{2\text{-eq}}$ km^{-1} per passenger.

3.4. Sensitivity Analysis

To address the inherent uncertainty associated with the baseline assumptions and to provide a more robust quantification of the environmental impact, a sensitivity analysis was conducted on the core parameters of the mobility model. This procedure is aimed at evaluating the stability of the carbon footprint estimates by observing how variations in key input variables influence the final emission totals, thereby identifying the primary drivers of environmental uncertainty within the Olympic context.

Specifically, three critical dimensions of the model were subjected to perturbation to account for potential deviations from the projected scenarios. First, the geographical distribution of visitors was tested by applying a variation of $\pm 20\%$ to the share of long-haul international arrivals. Given the high emission intensity of intercontinental aviation, this adjustment is necessary to assess the weight of global tourism demand on the overall carbon balance. Second, the modal split was reassessed by modifying the proportion of spectators utilizing private car transport by $\pm 20\%$. This variation reflects the potential volatility in the effectiveness of the planned collective transport infrastructure and the unpredictable behavioral responses of visitors to the logistical constraints of the alpine environment. Finally, the vehicle occupancy rate was adjusted from the baseline of 1.5 passengers to a range between 1.2 and 1.8. This variation acknowledges the social and logistical complexity of travel behavior during mega-events, where the efficiency of private mobility can significantly fluctuate.

4. Results

4.1. External Flows: Volume, Origin, and Modal Characteristics

Figure 2 shows the evolution of total attendance for Winter Olympic Games between 1980 and 2018, alongside the projected value for 2026. Salt Lake City 2002 and Vancouver 2010 recorded total flows exceeding two million people, while Torino 2006 and PyeongChang 2018 reached figures close to 1.5 million units. The historical data suggest a positive relationship between the number of events and total attendance, indicating that larger Olympic programs tend to involve higher numbers of participants. Although this relationship exhibits a relatively low coefficient of determination ($R^2 = 0.25$), it still indicates that event scale contributes to explaining variations in attendance.

When compared to this historical distribution, the estimated attendance for the Milano Cortina 2026 Winter Olympic Games (equal to 1,550,000) lies close to the fitted trend line. This alignment reinforces the consistency of the adopted estimation approach and supports the use of the derived attendance figure as a reliable baseline for modeling mobility flows and associated carbon emissions.

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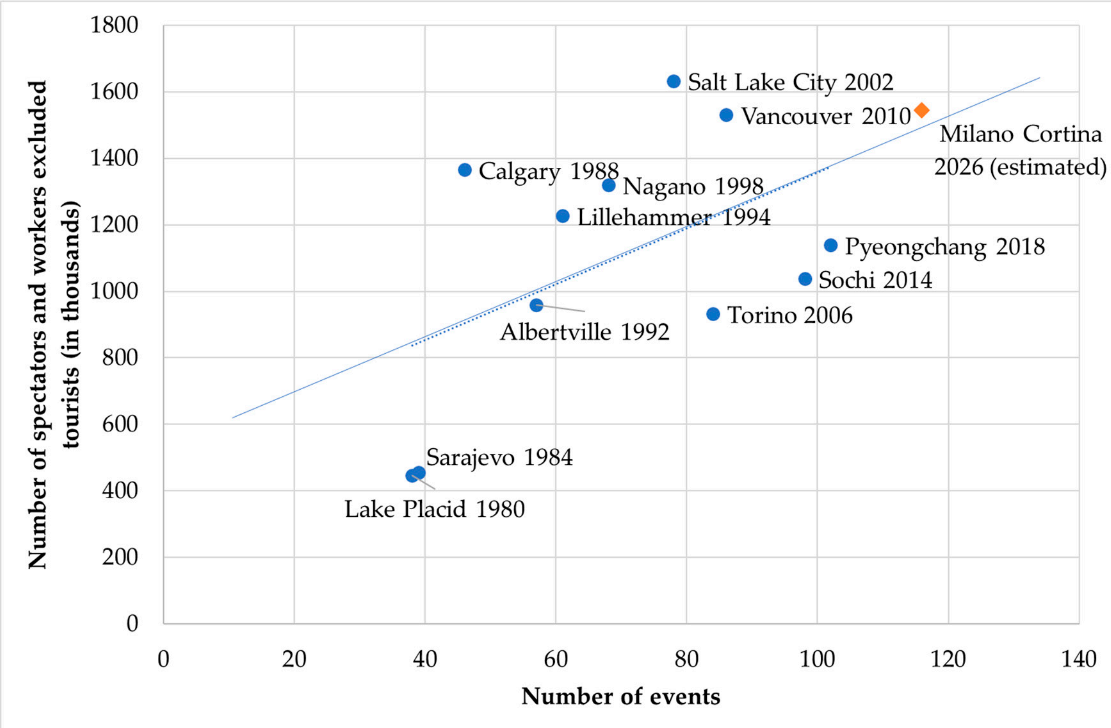

Figure 2. History of attendance figures for the Winter Olympic Games 1980–2018 (blue dots) and estimated attendance for the 2026 edition (orange diamond). The blue line shows the linear trend fitted to historical data (excluding 2026). (International Olympic Committee, 2024b; Davico, 2006).

The estimated figure of 1.55 million participants refers exclusively to accredited spectators and workforce with access to competition venues. However, large-scale mega-events typically generate an additional volume of visitors not captured by official attendance figures. Empirical evidence based on international tourism flows shows that hosting Olympic Games is associated with a statistically significant increase in tourist arrivals beyond accredited spectators, reflecting event-induced tourism driven by the global visibility and atmosphere of the event (Fourie & Santana-Gallego, 2011). In the case of Milano Cortina 2026, this additional component is estimated to increase the total number of people present in the Olympic macro-region to approximately 2 million (Cotrino, 2026). This adjustment accounts for three main factors: (i) the presence of visitors in public fan zones and entertainment areas (Weed, 2012), (ii) tourism flows motivated by the broader Olympic atmosphere rather than direct participation in events (Fourie & Santana-Gallego, 2011; Preuss, 2007; Reis et al., 2023), and (iii) accompanying travelers who contribute to overall mobility demand without being included in official spectator counts (Weed, 2012). Including this broader category of event-induced visitors allows for a more comprehensive estimation of mobility flows and associated environmental impacts.

The geographical distribution of spectators for the Milano Cortina 2026 Winter Olympic Games reflects an adaptation of the reference structure derived from the Paris 2024 Sustainability Report. The original categories of the Paris 2024 dataset were aggregated into three macro-groups to reflect the spatial scale relevant for mobility modeling. While the Paris model indicates a predominance of domestic spectators (approximately 66% of total visitors, Paris 2024 Sustainability Report, International Olympic Committee, 2024a), the adjusted distribution for Milano Cortina 2026 shows a slightly higher share of visitors originating from Italy and neighboring countries, estimated at approximately 70% (Figure 3). The remaining share of spectators is attributed to medium- and long-haul markets, accounting for approximately 20%

and 10% of total attendance, respectively. This distribution reflects the expected structure of demand for winter sports events, where European markets play a dominant role and long-haul travel represents a smaller, though still significant, component of total mobility flows. Overall, the resulting geographical segmentation maintains the general structure observed in the Paris 2024 dataset (International Olympic Committee, 2024a), while incorporating adjustments consistent with the specific characteristics of a decentralized alpine event.

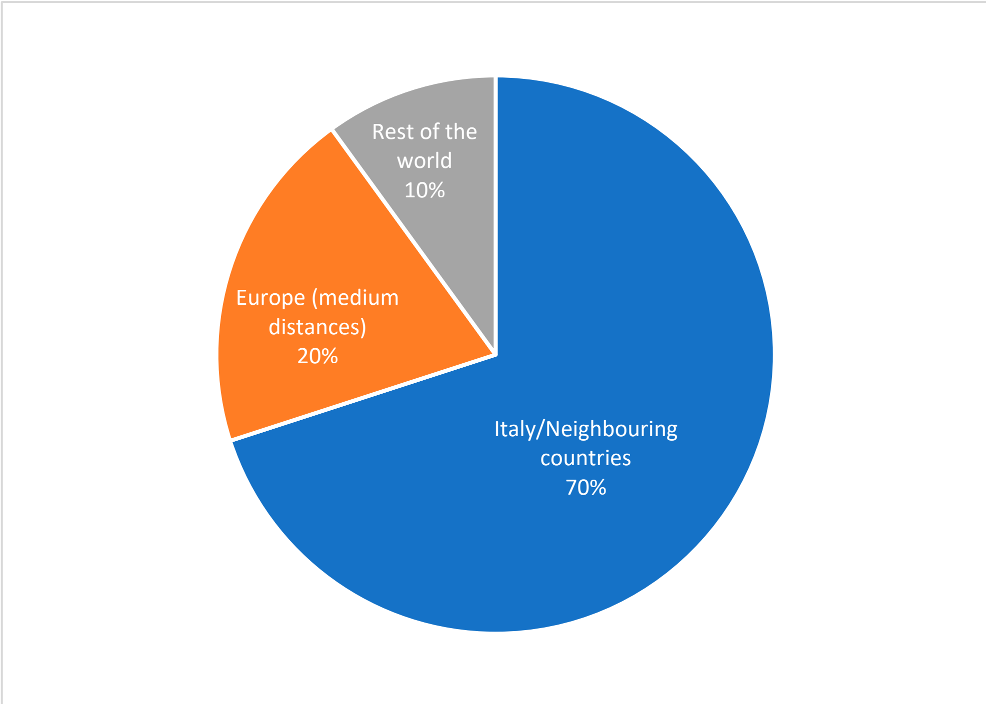

Figure 3. Estimated geographical distribution of spectators for the Milano Cortina 2026 Winter Olympic Games, based on an adapted model derived from the Paris 2024 Sustainability Report.

Additional support for this projection is provided by contemporary sectoral forecasts, particularly analyses based on event-related financial transactions (Gentili et al., 2025). These data indicate a substantial increase in international travel to Italy during the Olympic period, with air passenger volumes estimated to rise by approximately 160% compared to the corresponding period of the previous year. The expected growth is primarily driven by North American and Northern European markets, with the United States, Germany, and the United Kingdom accounting for a significant share of total demand. This geographical distribution is consistent with historical patterns of winter sports tourism and further supports the plausibility of the estimated attendance and origin structure adopted in this study.

The modal distribution of transport used to reach the Olympic macro-region varies significantly according to the geographical origin of visitors (Figure 4). For spectators traveling from Italy and neighboring countries, mobility is characterized by a diversified modal mix, with private cars accounting for approximately 50% of trips, followed by rail transport (30%), short-haul air travel (15%), and a minor contribution from bus transport (5%). In contrast, visitors from medium-distance European markets show a higher reliance on air transport (50%), with road transport (40%) and rail (10%) playing secondary roles. For long-haul international visitors, air transport represents the only viable option, accounting for 100% of travel flows. Overall, the results highlight a clear relationship between travel distance and modal choice, with increasing dependence on air transport as the distance from the Olympic region grows.

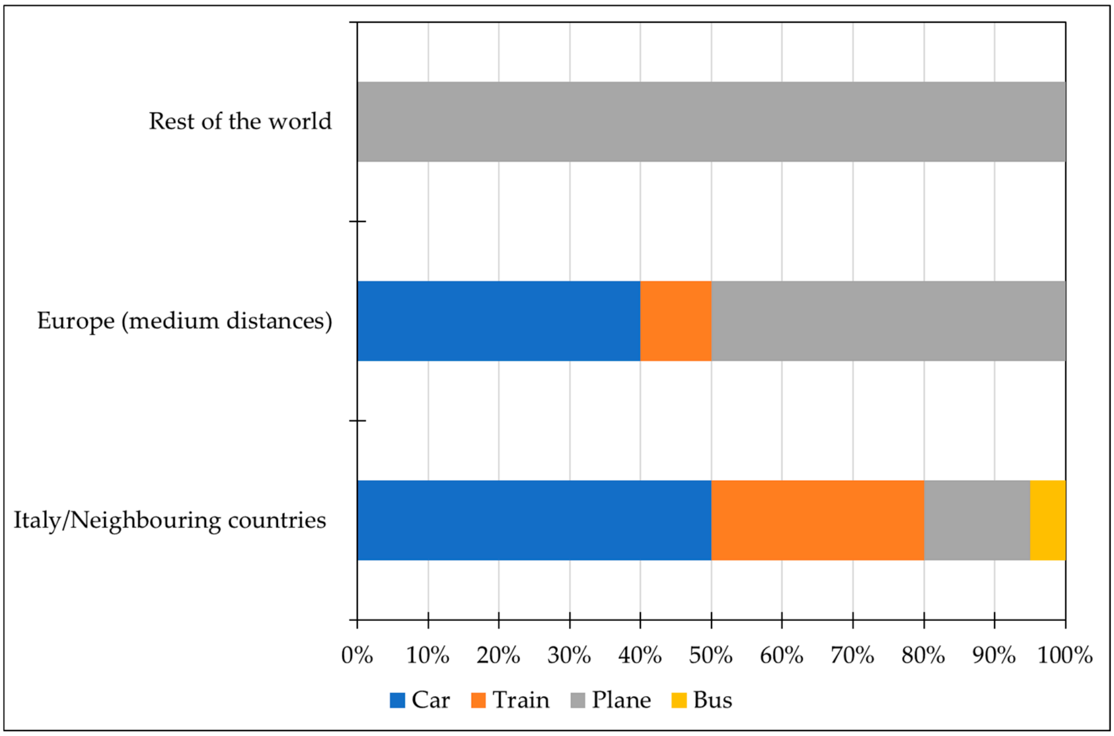

Figure 4. Modal split of transport modes used to reach the Milano Cortina 2026 Olympic region, by geographical origin of visitors. Percentages represent the relative contribution of each transport mode within each origin category.

4.2. Estimated Internal Flows Across the Olympic Clusters

The spatial distribution of visitors across the Olympic clusters reflects the polycentric structure of the Milano Cortina 2026 Games (Table 3 and Figure 5). The estimated allocation of people shows a strong concentration in a limited number of key nodes, with significant differences in the magnitude of flows across locations. The distribution of non-ticketed visitors is not uniform across clusters, reflecting differences in urban attractiveness and accommodation capacity, with a higher concentration in the Milan metropolitan area and more constrained volumes in alpine locations.

Table 3. Estimated spatial distribution of visitors (divided in spectators and tourists) across the Milano Cortina 2026 Olympic clusters.

Location	Number of Spectators	Number of Tourists (No Ticket)	Total Number of People
Milan	780,000	225,000	1,005,000
Cortina d’Ampezzo	180,000	90,000	270,000
Anterselva	190,000	9000	199,000
Tesero	180,000	9000	189,000
Livigno	100,000	45,000	145,000
Bormio	60,000	30,200	90,200
Verona	20,000	45,000	65,000
Predazzo	40,000	12,200	52,200
Total	1,550,000	450,000	2,000,000

The Milan cluster represents the primary hub, hosting approximately 1,000,000 people (50% of total attendance), and functions as both the main access gateway and the venue for indoor disciplines. Secondary clusters include Cortina d’Ampezzo and the Valtellina area (Bormio and Livigno), each attracting approximately 270,000 and 145,000 visitors, respectively. Intermediate volumes are observed in Val di Fiemme (Tesero and Predazzo) and Antholz (Anterselva), while Verona, despite not hosting competitions, plays a role as a transport node and event location, with approximately 65,000 visitors.

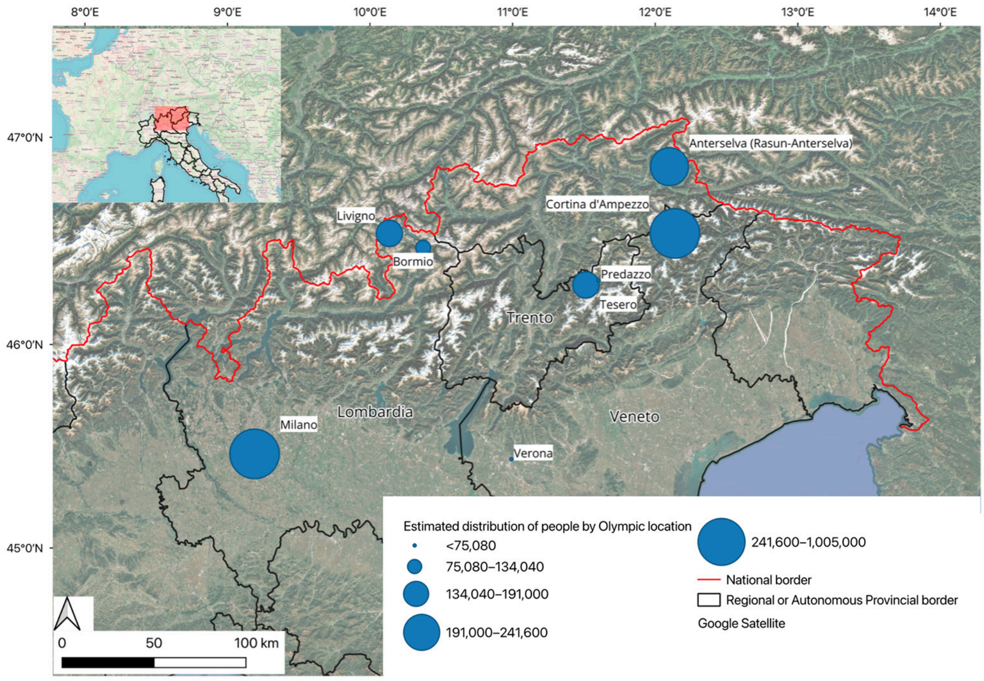

Figure 5. Estimated spatial distribution of visitors across the Milano Cortina 2026 Olympic clusters. Circle size is proportional to the total number of people (including both ticketed spectators and non-ticketed visitors) allocated to each location.

The total number of people considered in the analysis includes both accredited spectators and an additional share of non-ticketed visitors attracted by the event (Table 3). While these visitors contribute significantly to overall attendance and local demand, their mobility patterns are assumed to be more spatially concentrated within host locations compared to ticketed spectators attending multiple venues. The distribution of these internal movements between clusters was calculated through the proportional allocation framework described in Section 3.2, which distributes the total visitor baseline across locations based on the competition venue capacities (Table 1) and models the travel demand of spectators moving from primary hubs to peripheral venues.

Overall, the results highlight a highly uneven spatial distribution of flows, characterized by the coexistence of a dominant metropolitan hub and multiple smaller alpine clusters with lower but spatially concentrated attendance. This pattern reflects the combined influence of event allocation, venue capacity, and territorial configuration.

4.3. Mobility-Related $CO_{2\text{-}eq}$ Emissions for Milano Cortina 2026

The analysis of external mobility (i.e., referring to travel from places of origin to the Olympic macro-region) reveals a total estimated environmental impact of approximately 292,500 tonnes of $CO_{2\text{-}eq}$ (Figure 6). This value is strongly influenced by both the geographical origin of spectators and the distances involved, as well as by the modal distribution of transport.

Visitors from Italy and neighboring countries contribute approximately 71,976 tonnes of $CO_{2\text{-}eq}$, benefiting from shorter travel distances and a diversified modal mix that includes a substantial share of rail transport. The European segment generates approximately 74,960 tonnes of $CO_{2\text{-}eq}$, reflecting a higher reliance on air transport over medium distances. In contrast, long-haul international flows account for approximately 145,600 tonnes of $CO_{2\text{-}eq}$ due to the exclusive use of air transport.

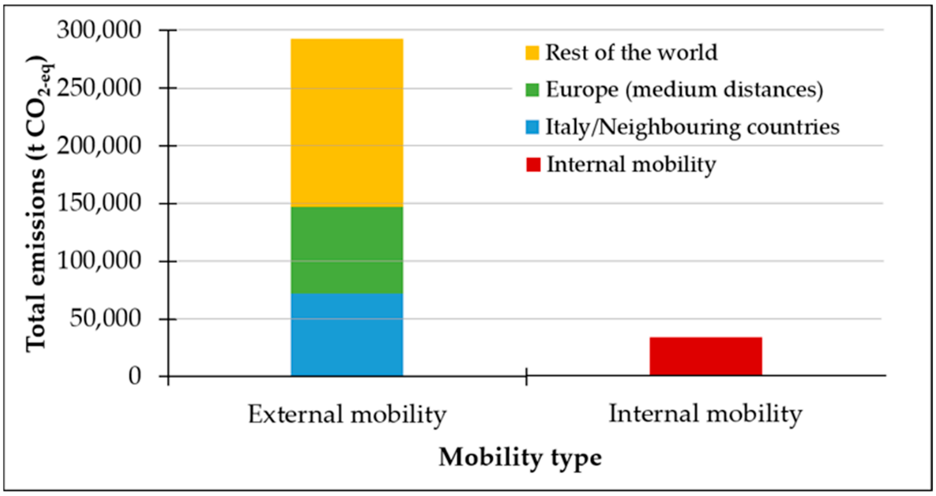

Figure 6. Estimated $CO_{2\text{-eq}}$ emissions associated with external and internal mobility flows. External mobility is disaggregated by geographical origin (Italy and neighbouring countries, Europe, and rest of the world), while internal mobility is shown as a separate component.

A comparison between the distribution of visitors and the corresponding share of emissions highlights a strong imbalance between flow magnitude and environmental impact. While visitors from Italy and neighboring countries account for approximately 70% of total attendance, they contribute only about 24.6% of total emissions. Similarly, the European segment represents around 20% of visitors but generates approximately 25.6% of emissions. In contrast, long-haul international visitors (representing only 10% of total attendance) account for nearly 50% of total emissions. This disproportion reflects the combined effect of long travel distances and the exclusive reliance on air transport for intercontinental mobility.

These results underline how the environmental impact of external mobility is driven more by distance and transport mode than by the absolute number of visitors.

Internal mobility within the Olympic clusters generates an estimated environmental impact exceeding 36,300 tonnes of $CO_{2\text{-eq}}$ (Figure 6 and Table 4), that is territorially concentrated and ecologically more sensitive. The distribution of emissions across the main transit corridors highlights the importance of specific inter-cluster connections, with the Milan–Cortina and Verona–Cortina routes representing the most significant contributions. The estimation of internal mobility considers only the subset of visitors involved in inter-cluster movements, resulting in a total of approximately 1,000,000 individuals contributing to internal flows, half of the total number of people involved in the Olympic Games. This distinction reflects the difference between total attendance and mobility-generating demand.

Table 4. Estimated carbon footprint resulting from internal mobility in the eight main directions.

Directions	Total Distance	Estimated People	Total Emissions (t $CO_{2\text{-eq}}$)
Milano–Cortina	820 km	116,100	6600
Verona–Cortina	520 km	174,200	6300
Milano–Livigno	460 km	155,900	5000
Milano–Anterselva	760 km	85,600	4500
Milano–Val di Fiemme	600 km	100,400	4200
Verona–Anterselva	460 km	128,400	4100
Verona–Val di Fiemme	300 km	150,700	3100
Milano–Bormio	400 km	88,700	2500
Total	-	1,000,000	36,300

Although private cars account for approximately 50% of internal movements, they are responsible for nearly 80% of total emissions in this category. In contrast, rail and bus transport contribute a smaller share of emissions relative to their use.

These findings highlight the disproportionate environmental impact of road-based mobility within the Olympic system.

A comparison between external and internal mobility highlights a pronounced imbalance in their contribution to total emissions. External mobility accounts for approximately 91% of total transport-related emissions, while internal mobility represents only about 9% (Figure 6). This contrast reflects the dominant role of long-distance travel in shaping the overall carbon footprint of the event, while internal flows, although limited in magnitude, are spatially concentrated within alpine environments.

To synthesize the environmental performance of the event, Table 5 provides an overview of the key efficiency metrics and localized carbon intensities derived from the mobility model. The total estimated transport-related carbon footprint of 328,800 tonnes of $CO_{2\text{-eq}}$ translates into an average of 0.164 tonnes of $CO_{2\text{-eq}}$ per individual visitor across the entire event population. However, a significant discrepancy emerges when disaggregating this figure by visitor type. Accredited spectators exhibit a significantly higher per capita impact (0.188 tonnes of $CO_{2\text{-eq}}$/person). These variations are structurally linked to the higher propensity of ticketed spectators to generate multi-destination travel itineraries across the geographically dispersed Olympic clusters, whereas non-ticketed visitors remain primarily stationary within their initial arrival hubs.

Table 5. Key environmental and mobility indicators for Milano Cortina 2026.

Indicator	Value
Total emissions (estimated)	328,800 t $CO_{2\text{-eq}}$
Average CO_2 per visitor	0.164 t $CO_{2\text{-eq}}$/person
Average CO_2 per spectator	0.188 t $CO_{2\text{-eq}}$/person
% emissions by mode	~75% air travel; ~20% private cars; ~5% other means of transport
Average external trip emissions	146.3 kg $CO_{2\text{-eq}}$
Average internal trip emissions	36.3 kg $CO_{2\text{-eq}}$

The aggregated modal share of emissions further highlights the dominant contribution of long-distance and individual road-based transit, with air travel accounting for approximately 75% of total carbon output and private cars generating around 20%, leaving all other collective and active transport modes to contribute a combined minor share of only 5%. On a trip-by-trip scale, this macro-level imbalance manifests as a stark contrast between spatial scales: the average external trip required to reach the Olympic macro-region generates 146.2 kg of $CO_{2\text{-eq}}$ per person, while an internal inter-cluster journey emits an average of 36.3 kg of $CO_{2\text{-eq}}$. Collectively, these indicators quantitatively demonstrate how the overall carbon profile of a polycentric mega-event is simultaneously dictated by global long-haul aviation choices and local private car reliance within the host territories.

In light of the identified carbon debt, this study conducted a "what-if" mitigation analysis to quantify the potential impact of targeted modal shift policies. Specifically, the scenario considers a 20% increase in rail transport usage (displacing a corresponding share of private car travel) for both external flows from neighboring regions and internal inter-cluster movements. The simulation reveals that such a shift would lead to a reduction of approximately 14,500 tonnes of $CO_{2\text{-eq}}$, representing a nearly 40% decrease in the emissions specifically generated by internal road mobility.

This finding highlights a key area for intervention for event planners: while the decentralized nature of the Games is a fixed geographical constraint, the carbon intensity of the resulting flows is highly elastic and dependent on the efficiency of the rail–road interface. Promoting rail accessibility not only mitigates the environmental burden but also serves as a strategic countermeasure to the "mobility paradox" inherent in polycentric events. Therefore, the implementation of strong incentives for collective transport should be considered a key requirement for reducing the gap between sustainability objectives and the operational reality of the 2026 Games. The mitigation scenario presented here should be interpreted as an exploratory assessment rather than a predictive transport policy outcome.

5. Discussion

This study proposes a conceptual framework to evaluate the environmental sustainability of decentralized mega-events, highlighting a systematic trade-off between infrastructure-related impacts and mobility-related emissions. While the adoption of a polycentric territorial model, such as that of Milano Cortina 2026, may reduce localized environmental impacts associated with the construction of new permanent venues and land consumption (Darcy & Taylor, 2013; Vrondou, 2023), it simultaneously increases the complexity and intensity of mobility demand.

The empirical evidence presented in this study demonstrates that mobility emerges as a major and often underestimated component of the environmental impact of decentralized mega-events. The spatial dispersion of competition venues extends travel distances, increases reliance on long-distance transport systems, and complicates the organization of collective mobility solutions, particularly in geographically constrained alpine environments. As a consequence, part of the environmental burden is displaced from fixed infrastructure toward highly dynamic transport flows.

Within this framework, the Milano Cortina 2026 case provides empirical verification of what has been broadly observed in regional planning as the tension between infrastructure minimization and transport expansion. While the spatial trade-off between local land-saving strategies and regional transport expansion is well established in the literature on transport geography and mega-event planning, this study uses the expression "paradox of decentralized sustainability" as a conceptual label to describe the empirical manifestation of this trade-off in the specific context of modern polycentric mega-events. In fact, this dynamic strongly echoes the spatial and logistical challenges observed in past regionalized mega-events. A clear historical precedent is represented by the Winter Olympic Games of Albertville 1992, where the extensive fragmentation of venues across separate alpine valleys similarly locked the event into highly inefficient transport patterns, multiplying vehicle-kilometers traveled due to the lower viability of continuous rail infrastructure (Chappelet, 2014). Beyond the Olympic scope, transport geography literature has widely conceptualized this friction as a spatial trade-off, demonstrating how polycentric configurations and territorial dispersion can systematically act as impact multipliers by increasing average travel distances, thereby offsetting the environmental benefits gained through local localized land-saving strategies (Chen et al., 2023). The novelty of this study lies not in proposing a completely new theoretical construct, but in demonstrating how this expected tension materializes when a mega-event scales across 22,000 km^2 of topographically constrained territory. Our findings transition this dynamic from a qualitative assumption to a quantifiable spatial reality, showing that decentralization is not a universal sustainability solution but a highly volatile spatial configuration whose net environmental performance is contingent upon local accessibility boundaries and existing low-carbon transport networks.

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5.1. Interpretation of the Main Findings

The results of this study show that the carbon footprint of mobility associated with Milano Cortina 2026 is characterized by a pronounced imbalance between external and internal flows. External mobility accounts for approximately 91% of total transport-related emissions, confirming that long-distance access to the Olympic macro-region, particularly by air transport, represents the primary driver of the overall carbon footprint.

At the same time, the smaller quantitative contribution of internal mobility should not be interpreted as environmentally marginal. Internal flows are spatially concentrated within alpine valleys and mountain corridors, where transport capacity is inherently constrained and ecosystems exhibit high sensitivity to additional anthropogenic pressure (Hooper et al., 2017; Leone et al., 2014; Orsi et al., 2020; Zhang et al., 2026). In this sense, the decentralized structure of Milano Cortina 2026 generates a dual environmental challenge: emissions are dominated by long-distance travel at the global scale, while environmental pressure is territorially concentrated within fragile host regions. While the overwhelming dominance of long-distance aviation emissions and the carbon intensity of private vehicle transit align with established mega-event impact patterns and might appear predictable at a macro-scale, the critical value of these quantified metrics lies in their scalar and spatial intersection. The predictability of global transit volumes often obscures the highly volatile localized pressures within decentralized systems. By precise quantification, this study demonstrates that internal mobility, despite representing only 9% of the estimated total carbon footprint, induces a highly disproportionate ecological pressure due to its high geographical concentration within environmentally sensitive alpine corridors. Consequently, the contribution of this data is not the discovery of aviation's high carbon footprint per se, but the empirical mapping of how global tourism demand scales down into severe, localized socio-technical and environmental bottlenecks, providing a spatially explicit perspective that is often overlooked in studies of more centralized mega-events. The novelty of our findings therefore lies less in the identification of the dominant emission sources and more in the quantification of how those emissions are spatially redistributed within a decentralized mountain event system.

These findings reinforce the idea that the environmental sustainability of mega-events cannot be evaluated solely through venue-related impacts or land-use reduction strategies. The Milano Cortina case demonstrates that territorial configuration and mobility systems play a decisive role in shaping the overall carbon footprint of decentralized events. From a governance perspective, these findings highlight some of the challenges associated with recent Olympic reforms, such as the International Olympic Committee's "New Norm" (Müller et al., 2021). While the New Norm explicitly encourages the utilization of existing facilities scattered across vast regions to minimize financial debt and localized land-use impacts, the resulting territorial structure shifts the fiscal and environmental burden onto regional transport networks. This operational reality suggests that tensions may emerge between decentralized event governance models and local environmental carrying capacities. For future Olympic planning models, this imbalance demonstrates that venue flexibility cannot be evaluated in isolation from regional transport geometry; governance frameworks could benefit from incorporating multi-scalar carbon budgeting approaches on transport logistics during the initial venue allocation phase, treating spatial accessibility as a fundamental ecological constraint rather than a secondary logistical challenge.

5.2. Sensitivity Analysis

The results of the uncertainty associated with the baseline assumptions demonstrate that the model is particularly sensitive to the share of long-haul travel, which remains the dominant contributor to the overall carbon footprint, whereas variations in internal modal split and occupancy rates show a more contained impact on the total figures. By systematically recalculating the greenhouse gas emissions under these alternative configurations, the study identifies a range of potential outcomes that validate the robustness of the baseline results.

Specifically, perturbing the geographical distribution reveals that a +20% increase in the long-haul international market elevates aviation emissions for this segment to 174,720 tonnes of $CO_{2\text{-eq}}$, while a −20% reduction lowers them to 116,480 tonnes of $CO_{2\text{-eq}}$. When assessing the modal split, a +20% increase in private car usage drives road transport emissions up to 107,892 tonnes of $CO_{2\text{-eq}}$, whereas a −20% contraction reduces them to 56,388 tonnes of $CO_{2\text{-eq}}$. Finally, shifting the vehicle occupancy rate from the baseline of 1.5 passengers to a low-efficiency scenario of 1.2 passengers results in private mobility emissions of 102,367 tonnes of $CO_{2\text{-eq}}$, while a high-efficiency scenario of 1.8 passengers compresses this impact to 68,244 tonnes of $CO_{2\text{-eq}}$.

Accounting for these variations, the total estimated emissions for the event range between 260.6 and 396.9 kt $CO_{2\text{-eq}}$ depending on the underlying assumptions. This scenario-based assessment ensures that the findings remain interpretatively valid across different socio-technical and logistical conditions, providing a comprehensive interval of the event's potential environmental burden.

5.3. Comparison with Previous Studies and Other Mega-Events

The estimated emissions for Milano Cortina 2026, approximately 326,000 tonnes of $CO_{2\text{-eq}}$, can be contextualized through comparison with other sport mega-events, although such comparisons must be interpreted cautiously due to differences in scale, duration, and accounting boundaries.

Existing studies consistently identify mobility as the dominant contributor to the carbon footprint of sporting events. In football, for example, spectator and team travel frequently account for the largest share of emissions, often exceeding 60% of total impacts and reaching even higher values in elite competitions due to the extensive use of air transport (Tóffano Pereira et al., 2019). This structural pattern closely parallels our macro-level findings for Milano Cortina 2026, where long-distance air travel generates approximately 75% of the total carbon output. However, a key distinction emerges in the nature of the mobility demand: while in elite football leagues the carbon intensity is systematically driven by frequent, short-to-medium-range flights taken by teams and compact supporter groups across a dense stadium network, the Olympic footprint is dominated by one-off, intercontinental long-haul spectator flights combined with a highly fragmented regional transit framework. Spectator-focused analyses further confirm the relevance of transport mode and travel distance, with Dosumu et al. (2017) estimating total emissions of 56,237 tonnes of $CO_{2\text{-eq}}$ for football spectators in England (or less than 0.05% of total transport emissions in England), and the average travel emission among the participants of 4.74 kg $CO_{2\text{-eq}}$ per game. Loewen and Wicker (2021) showed that individual fan carbon footprints can be strongly influenced by transport mode, particularly private cars and air travel. In Germany, they calculated that the average seasonal carbon footprint of a Bundesliga fan amounted 311.1 kg $CO_{2\text{-eq}}$, with car travel accounting for 70% of these emissions. As far as clubs are concerned, Tóffano Pereira et al. (2019) calculate that English Premier League clubs generate 56,724 kg of $CO_{2\text{-eq}}$ on average per season, with most of this (around 85%) generated through teams flying to and from fixtures.

At a larger scale, global events such as the FIFA World Cup Qatar 2022 have been associated with total emissions in the order of 3.6 million tonnes of $CO_{2\text{-eq}}$, largely driven by international travel and transport-related activities (Lygdopoulos, 2023). Similarly, global sport systems such as Formula 1 have been estimated to generate between 170,000 and

250,000 tonnes of $CO_{2\text{-eq}}$ per season, depending on the reference year and accounting methodology (Formula 1, 2020). A large share of these emissions is attributable to logistics and travel. Together, these examples confirm that mobility-related emissions represent a central component of contemporary sport mega-events.

When bench-marked specifically against previous Winter Olympic configurations, the structural impact of the Milano Cortina model becomes empirically distinct. Historically, more centralized Winter Games, such as Vancouver 2010 or Sochi 2014, concentrated their environmental footprints within compact urban-to-mountain corridors. In those cases, the proximity between high-capacity accommodation hubs and competition venues allowed for dedicated mass-transit solutions, compressing internal mobility to a marginal fraction of the event's total carbon budget. Conversely, the polycentric layout of Milano Cortina closely mirrors the highly dispersed model of Albertville 1992, where the fragmentation of events across distinct alpine valleys triggered severe systemic inefficiencies in transport logistics (Chappelet, 2014), multiplying vehicle-kilometers traveled due to the lower viability of unified rail connections. Our estimate of 326,000 tonnes of $CO_{2\text{-eq}}$ validates this structural trend, illustrating that while decentralized configurations avoid the intensive construction-related footprints seen in Sochi, they lock the event into an inflated operational mobility baseline, establishing a critical precedent for future regionalized winter games.

Beyond emission patterns, the inclusion of non-ticketed visitors also requires interpretation within the broader literature on mega-events and tourism demand. Mega-events are widely recognized as generating visitor flows that extend beyond formal spectatorship (Müller, 2015). Empirical evidence shows that this additional demand translates into increased tourism flows during Olympic years, which are often underestimated in conventional impact assessments (Fourie & Santana-Gallego, 2011; Reis et al., 2023). Recent analyses of the Paris 2024 Olympic Games further support this perspective, indicating that tourism demand during mega-events includes a broader range of visitors attracted by the event environment and associated activities, rather than solely by participation in competitions (Parkins, 2024). This is consistent with econometric evidence demonstrating that Olympic Games lead to a significant increase in international tourist arrivals during the event year, reflecting tourism flows not directly linked to attendance at competition venues (Fourie & Santana-Gallego, 2011). In this context, the inclusion of non-ticketed visitors reflects a broader understanding of tourism demand, encompassing experiential and context-driven motivations, whereby visitors are attracted by the overall atmosphere and socio-cultural environment of the host destination (Preuss, 2007). This approach is aligned with recent reviews on sport mega-event legacies, which highlight that tourism-related impacts often extend beyond direct event participation and are not fully captured by official attendance metrics (Reis et al., 2023).

In this perspective, the dominance of external mobility observed in the Milano Cortina 2026 case (accounting for approximately 91% of total emissions) can be interpreted as a consistent manifestation of a broader pattern, whereby long-distance travel, and especially air transport, represents the main driver of environmental impact in sport mega-events.

However, the Milano Cortina case also highlights a distinctive feature related to its polycentric territorial configuration. Unlike more centralized events, such as Paris 2024, where accessibility is supported by dense metropolitan transport networks, the decentralized structure of the Italian Games increases the complexity of mobility patterns and shifts part of the environmental burden toward regional transport systems. This highlights that, while the dominance of travel-related emissions is a common feature across sport mega-events, territorial configuration represents an additional and often overlooked determinant of environmental impact.

5.4. Methodological Limitations and Uncertainties

The scientific validity of carbon footprint assessments requires a careful evaluation of the uncertainties inherent in the estimation process. In this study, uncertainty primarily arises from the use of secondary data and projected mobility flows, which introduces an unavoidable margin of approximation.

A key source of variability lies in the selection of emission factors. Although derived from established scientific literature, these factors may vary depending on the reference database and the technological characteristics of transport systems. In the case of aviation, additional uncertainty is associated with the estimation of radiative forcing effects, whose quantification remains subject to ongoing scientific debate (Bianco et al., 2026; Boucher et al., 2021; Jungbluth & Meili, 2019).

Internal mobility estimates are also affected by assumptions related to vehicle occupancy rates and the actual adoption of intermodal transport solutions by visitors. Furthermore, the definition of system boundaries and the allocation of per capita emissions inherently involve a degree of interpretive subjectivity.

Finally, uncertainties may arise from potential behavioral changes during the event, such as congestion-induced route modifications or rebound effects, which are difficult to predict based on historical analogues.

For these reasons, the present analysis should be interpreted as a probabilistic estimation of environmental impact rather than an exact quantification. Transparency regarding these limitations is essential to ensure the robustness of the results and to support informed decision-making in the context of sustainable mobility planning.

5.5. Implications for Planning and Sustainable Mobility

The results of this study highlight a structural tension between the spatial organization of the Milano Cortina 2026 Olympic Games and the requirements for low-carbon mobility. The combination of geographically dispersed clusters and limited intermodal accessibility suggests the persistence of a mobility model that remains strongly dependent on road transport, in contrast with decarbonization objectives (Gogishvili & Müller, 2026; Jones et al., 2022; Pereira, 2018; Sang et al., 2026).

Within this framework, the findings support what can be defined as a "paradox of decentralized sustainability". While the reuse of existing venues reduces land consumption and construction-related impacts (Francis et al., 2023; Gold & Gold, 2021; Wergeland & Hognestad, 2021), these benefits may be offset by the increased emissions associated with connecting geographically distant clusters (Ballarano et al., 2022; Lopes Dos Santos et al., 2022). Even when infrastructure-related impacts are minimized, the spatial configuration of mega-events plays a decisive role in determining overall emissions, as increased distances between venues directly translate into additional mobility-related carbon outputs (Gogishvili & Müller, 2026). Reviews on land-use and spatial planning consistently show that spatial dispersion increases transport demand and related carbon emissions, undermining low-carbon planning objectives (Wang & Jin, 2025). In this sense, territorial dispersion may act as an impact multiplier rather than a mitigation strategy, particularly in mountain regions characterized by limited accessibility and high environmental sensitivity (Arcidiacono et al., 2024; Hanly & McDowell, 2025).

These results emphasize the need to integrate carbon footprint assessments into the early planning stages of mega-events, making intermodal accessibility a key criterion in event design (Gogishvili & Müller, 2026). Future research should focus on the ex post monitoring of actual mobility flows to validate predictive models and refine key parameters such as modal split and vehicle occupancy rates (Ballarano et al., 2022; Kassens-Noor et al., 2015). In addition, further investigation is required to assess the

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long-term effects of Olympic-related mobility patterns on regional transport systems in alpine contexts characterized by structural constraints and high environmental sensitivity (Arcidiacono et al., 2024). Crucially, mitigating this carbon debt requires shifting from purely top-down structural interventions to bottom-up behavioral management targeting the event participants. To actively encourage low-impact travel behavior among tourists, future decentralized mega-events must deploy targeted behavioral interventions integrated into the digital ticketing and informational infrastructure. For instance, event organizers should implement "green nudging" strategies within official applications, such as bundling venue tickets with mandatory public transport passes or displaying real-time carbon footprints alongside alternative routing options. Furthermore, reward-based gamification frameworks (where tourists earn points or discounts on corporate merchandising and regional hospitality for choosing rail over private vehicles) can convert abstract environmental awareness into quantifiable shifts in collective mobility. In polycentric layouts, individual traveler choices collectively dictate local environmental pressure; empowering tourists with active behavioral choices can significantly flatten the emission peaks within fragile alpine valleys. In this dynamic, Destination Management Organizations (DMOs) play a pivotal role in operationalizing these behavioral shifts, transitioning from mere promotional bodies to active flow managers. Since eliminating spectator mobility across fragmented valleys is unfeasible, DMOs must deploy specific precautions to mitigate transport-related pressures. First, DMOs can design targeted marketing strategies aimed at lengthening the average duration of stay, converting high-mobility day-trippers into stationary, multi-day visitors, which effectively reduces the per diem transit frequency between clusters (Peeters et al., 2018). Second, to prevent spontaneous road travel during gaps in the sporting calendar, DMOs should curate and promote decentralized "micro-itineraries" focused on slow mobility (such as walking or e-bike paths) and hyper-local cultural assets within the immediate vicinity of the accommodation hubs. By structurally filling the visitor's leisure window with low-carbon, localized experiences, DMOs can systematically redirect tourist behavior away from private car usage, preserving the immediate carrying capacity of fragile mountain ecosystems while maximizing regional economic retention.

Adaptation strategies, such as snow management and snow farming (Senese et al., 2020), may contribute to reducing mobility demand by enabling competitions to be hosted in more accessible locations (Scott et al., 2023). However, their environmental effectiveness depends on minimizing their own carbon footprint, particularly in relation to energy use and material inputs (Schmitt et al., 2025). The environmental effectiveness of snow management strategies critically depends on their energy intensity, as artificial snow production and storage require substantial energy inputs that can significantly increase carbon emissions if not supplied by low-carbon sources (Abegg et al., 2021).

From a quantitative perspective, the estimated emissions of approximately 326,000 tonnes of $CO_{2\text{-eq}}$ represent a significant impact when contextualized across multiple scales. This volume is equivalent to the annual direct carbon footprint of over 58,000 Italian citizens (Senese et al., 2024) and is comparable to the emissions associated with certain global sport systems, highlighting the relevance of mobility-related emissions even in events of limited duration. From a consumer behavior perspective, the magnitude of these emissions is comparable to the production of over 59 million medium-sized polyester t-shirts, each estimated to emit 5.5 kg of CO_2, or the logistics associated with the long-distance air freight of approximately 138 million individual parcels from international hubs.

Overall, these findings suggest that the environmental sustainability of mega-events is strongly dependent on mobility systems. Reducing emissions requires not only limiting long-distance travel but also rethinking spatial configurations and strengthening collective transport solutions, particularly in geographically constrained and environmentally sensitive regions.

6. Conclusions

This study provides an integrated assessment of mobility-related carbon emissions associated with the Milano Cortina 2026 Winter Olympic Games, highlighting the implications of a decentralized territorial configuration for environmental sustainability. The results show that total emissions amount to approximately 326,000 tonnes of $CO_{2\text{-eq}}$, with a pronounced imbalance between external and internal mobility. External flows, primarily driven by long-distance travel, account for about 91% of total emissions, while internal mobility, although quantitatively limited, generates spatially concentrated impacts within environmentally sensitive alpine regions.

These findings confirm the existence of a "paradox of decentralized sustainability". While the reuse of existing infrastructure reduces construction-related impacts, the geographical dispersion of venues increases mobility demand and shifts the environmental burden toward transport systems. In this sense, the spatial organization of the event emerges as a key determinant of its overall carbon footprint.

The study contributes to the literature by proposing a methodological framework that integrates attendance estimation, spatial allocation, and mobility modeling in the analysis of decentralized mega-events. By advancing this methodology, the study expands the theoretical understanding of mega-event lifecycles, suggesting that transit networks may play a more significant role than static infrastructure in defining the ecological footprint of decentralized mega-events. This approach allows for a more comprehensive understanding of the relationship between territorial configuration and mobility-related emissions.

From a planning perspective, the results underline the importance of integrating carbon footprint assessments into the early design of mega-events, with particular attention to intermodal accessibility and spatial layout. In terms of policy implementation, these findings demonstrate that achieving substantial emission reductions would require coordinated transport measures, such as mandatory rail-incentive packages and measures aimed at limiting private vehicle dependence during the event. Future research should focus on the ex post validation of mobility patterns during the event and on the long-term legacy effects of Olympic-related mobility systems in mountain regions.

Overall, the Milano Cortina 2026 case demonstrates that, in the absence of efficient and low-carbon transport systems, territorial dispersion may act as a driver of environmental impact rather than a strategy for sustainability, particularly in fragile alpine ecosystems. Ultimately, these findings suggest that decentralization alone cannot be considered a guarantee of sustainability unless host regions structurally decouple spectator mobility from carbon-intensive transport systems. These findings are relevant not only for Milano Cortina 2026, but for future mega-events adopting decentralized territorial models in environmentally constrained regions.

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