# Inter-Village Cultural Mobility: Towards a Sustainable Cultural Metro Model in the Castelli Romani

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***Abstract*—Tourism in peri-urban cultural landscapes is often characterized by high car dependency, resulting in congestion, pollution, and a diminished visitor experience. The Castelli Romani area near Rome exemplifies this challenge: despite its rich cultural and natural heritage, over 65% of tourists access the region by private car, causing significant $CO_2$ emissions, noise, and parking saturation. To address these issues, this paper introduces the concept of *Inter-Village Cultural Mobility*, which extends the *Cultural Metro* model from urban heritage contexts to a network of villages connected through sustainable ring routes. A web-based platform developed with *LeafletJS* enables interactive visualization of routes and comparative assessment between car-based and bus/trekking options, also contributing to the Human–Computer Interaction (HCI) domain. Preliminary simulations on a representative ring route indicate a 65% reduction in $CO_2$ emissions, an increase in accessibility from 0.58 to 0.91, and 47% integration with trekking networks. Usability tests with twelve participants confirmed the added value of interactive visualizations in supporting visitor decision-making. This study contributes to research in sustainable transport and digital tourism by integrating methodological formalization, simulation-based evaluation, and user-centered design. Future work will focus on expanding empirical validation, optimizing routing strategies, and exploring scalability to other peri-urban cultural destinations.**

***Keywords-Sustainable Mobility; Cultural Tourism; Genetic Algorithms; Urban and Regional Planning.***

## I. INTRODUCTION

Tourism in the metropolitan area of Rome is increasingly constrained by fragmented mobility infrastructure and a heavy reliance on private vehicles. Recent data indicate that more than 65% of the residents of the metropolitan region of Rome use private cars as their primary mode of transport [1]. In suburban and peri-urban areas such as the Castelli Romani, this dependency translates into recurrent traffic congestion, particularly on weekends and during major tourist events, generating negative impacts for both residents and visitors. Despite its wealth of cultural, archaeological, and natural assets, the Castelli Romani lacks a coherent and sustainable mobility framework capable of fully supporting its tourism potential. Furthermore, the 2024 Mobility Report by Città Metropolitana di Roma Capitale underscores a structural mismatch between existing transportation planning and the actual mobility flows of residents and tourists, emphasizing the need for multimodal and human-centered strategies, such as those piloted in the Biovie Project [2]. In this context, developing culturally guided, non-private transport systems emerges as a key requirement to improve accessibility, reduce environmental impacts, and foster sustainable tourism development. The goal of this work is to design and evaluate a framework that integrates ring shuttle routes, pedestrian/trekking connections, and a digital cultural guide. Unlike previous operational proposals, we emphasize a systematic methodology linking transport optimization with cultural tourism value. This work builds upon the concept of the "Cultural Metro", introduced in our previous publication [3] , where we proposed a metaphorical and infrastructural model of a metrolike system guiding tourists through a structured sequence of Cultural Points of Interest (POIs) across Rome. The Cultural Metro model is designed to integrate mobility and heritage, using intermodal transport lines adapted to cultural routes and supported by technological tools for exploration and participation. The remainder of this paper is organized as follows. Section II reviews the related work and state of the art in sustainable cultural tourism, examining existing approaches to mobility integration, routing optimization, and digital platform design, while identifying key gaps addressed by our research. Section III presents the methodology, detailing the problem definition, POI selection criteria, route design algorithms, sustainability-oriented indicators (SOR analysis), and the development of the interactive digital platform. Section IV introduces the Castelli Romani case study, describing the study area, ring route configuration, passenger demand assumptions, and integration with existing trekking networks. Section V reports the results and discussion, including routing optimization outcomes, comparative SOR analysis between car-based and multimodal transport, user interaction findings from preliminary usability testing, and a critical assessment of the approach's potential and limitations. Finally, the paper concludes with directions for future research and empirical validation.

## II. Related Work and State of the Art

The relationship between tourism mobility and sustainability has been widely addressed in transportation and urban planning research. Previous studies demonstrate that the predominance of car-based travel in cultural and peri-urban destinations generates congestion, environmental externalities, and accessibility inequities [4][5]. Approaches to mitigate these impacts include park-and-ride schemes, shared mobility services, and heritage bus circuits, with varying degrees of success depending on integration with local contexts [6][7].

Recent works in sustainable cultural tourism emphasize the importance of connecting Points of Interest (POIs) into coherent, multimodal itineraries that combine transport efficiency with visitor experience [8]. Projects such as the Alpujarra Cultural Routes in Spain or the Lake District Heritage Transport in the UK demonstrate that circular and ring-based routes can reduce car dependency, while enhancing thematic and narrative coherence of tourist visits [9]. However, these initiatives often remain operational or promotional, lacking a structured methodological framework for evaluating sustainability outcomes.

From a technological perspective, digital platforms for cultural mobility increasingly leverage GIS data, routing algorithms, and web mapping libraries (e.g., OpenStreetMap, LeafletJS). While these tools are effective for visualization, the literature highlights the need for usability studies and decision-support features to ensure real adoption by visitors and stakeholders [10]. Human-computer interaction (HCI) approaches in tourism systems show that interactive route comparison and ecological impact visualization can significantly influence user choices [11].

Despite these advances, gaps remain in the integration of:

- Empirical problem definition (e.g., quantified car dependency and emissions in specific cultural landscapes),
- Formalized methodology combining routing algorithms with sustainability indicators,
- Evaluation frameworks that compare car-based mobility with multimodal alternatives through measurable metrics ($CO_2$ reduction, accessibility, integration with walking/trekking).

The present work addresses these gaps by extending the Cultural Metro model to the inter-village scale, combining ring bus routes with trekking connections in the Castelli Romani. Unlike previous case studies, our approach introduces a structured Sustainability-Oriented Routing (SOR) analysis and a digital platform with interactive impact assessment, contributing both to transportation research and to digital tourism innovation.

## III. Methodology

The proposed model of *Inter-Village Cultural Mobility* aims to reduce private car dependency in the Castelli Romani area by designing circular bus routes integrated with trekking paths. The methodology is structured in four main steps.

### A. Problem Definition

Current surveys and regional mobility data indicate that approximately 65% of tourists in Castelli Romani reach Points Of Interest (POI) by private car, generating congestion, parking pressure, and $CO_2$ emissions. The objective of the proposed system is to offer sustainable alternatives through multimodal transport (bus + walk/trekking), while preserving accessibility to cultural and natural sites.

### B. Selection of Points of Interest (POIs)

POIs were selected according to three criteria:

1) **Cultural-historical relevance**: UNESCO sites, archaeological areas, and historical villas;
2) **Connectivity with existing trekking routes**: CAI network and regional park trails;
3) **Accessibility from villages with public transport hubs**.

The resulting network includes 12 villages and 18 POIs, structured into three ring routes.

### C. Route Design and Algorithmic Approach

Routes were generated using Google Maps Distance Matrix API and OpenStreetMap data, applying a greedy algorithm for minimization of travel time between consecutive POIs, while ensuring loop closure. Although greedy routing is a standard approach, its novelty lies in the integration of cultural relevance as a weighted parameter in the path selection.

### D. Sustainability-Oriented Indicators (SOR Analysis)

To evaluate the impact of the system, three indicators were defined:

- **$CO_2$ Emissions ($kgCO_2$)**: calculated from kilometers travelled by bus compared to car-based mobility (average emission factor: 0.18 $kgCO_2$/km per passenger);
- **Accessibility Index (AI)**: ratio between POIs reachable by public transport versus total POIs;
- **Integration Score (IS)**: proportion of routes overlapping with trekking paths, enhancing multimodality.

These indicators allow for a comparative analysis between current car-based mobility and the proposed model.

### E. Digital Platform

A LeafletJS-based web interface was implemented to visualize ring routes, POIs, and trekking connections. Compared to standard web mapping solutions, the platform integrates an interactive accessibility calculator: users can select a starting village and visualize alternative routes by car versus bus/trekking, with estimated travel time and $CO_2$ footprint.

The system, implemented with `LeafletJS`, allows interactive exploration of ring routes, Points of Interest (POIs), and their connections with nearby public transport stations and parking areas. Additional features include dynamic chart visualization of passenger flows and visitor demand profiles.

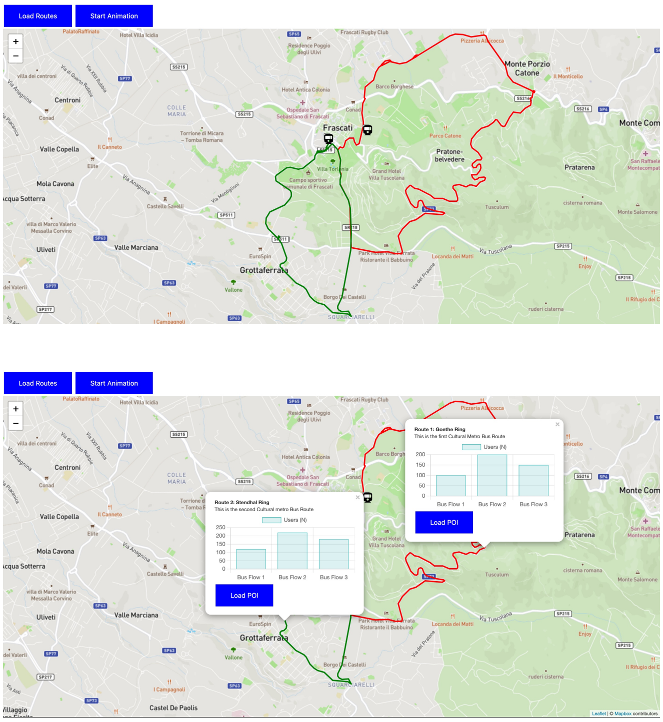


Figure 1. Prototype of the interactive web interface for route visualization.

## IV. Case Study: Castelli Romani

The Castelli Romani area, located approximately 20 km southeast of Rome, represents an emblematic peri-urban cultural landscape where historical villages, archaeological remains, and natural parks coexist with high tourist flows. The case study was selected because of its strong dependence on private cars and the potential for integrating sustainable cultural mobility solutions.

### A. Study Area and Context

The area includes twelve historical villages such as Frascati, Albano Laziale, Castel Gandolfo, and Nemi, distributed around the Albano volcanic lakes and the Regional Park of Castelli Romani. Tourism demand is characterized by day-trips from Rome, seasonal excursions, and cultural itineraries. Surveys conducted in 2023 reveal that over 65% of visitors arrive by private car, generating congestion in town centers and parking saturation near main Points of Interest (POIs).

### B. Ring Route Configuration

Based on the methodology described in Section 3, three circular bus routes were designed:

- **Northern Ring**: connecting Frascati, Monte Porzio Catone, and Tusculum archaeological area;
- **Central Ring**: covering Castel Gandolfo, Marino, Albano Laziale, and the Albano Lake perimeter;
- **Southern Ring**: linking Nemi, Genzano di Roma, and Ariccia, with integration to trekking routes around the Nemi Lake.

Each ring includes 6–8 stops, with 2–3 cultural POIs within walking distance of each stop. Distances between villages range from 3 to 7 km, making the configuration suitable for short-distance shuttle services.

### C. Passenger and Demand Assumptions

For simulation purposes, shuttle capacity was set between 15 and 20 passengers. Demand profiles were estimated from tourism statistics and local surveys, indicating a daily average of 5–12 passengers per segment during weekdays and 15–20 during weekends. These values represent realistic load factors for pilot implementation.

### D. Integration with Trekking and Cultural Routes

The Castelli Romani Regional Park includes more than 150 km of trekking and walking paths, many of which intersect the proposed bus stops. Integration with these routes provides the opportunity for multimodal itineraries, where visitors can alternate between short bus rides and trekking stages. This combination enhances both environmental sustainability and visitor experience, supporting the narrative coherence of cultural itineraries.

## V. Results and Discussion

This section presents preliminary results obtained from the simulation of the proposed Inter-Village Cultural Mobility system applied to the Castelli Romani area. Results are structured around three main outputs: (i) performance of the routing optimization, (ii) sustainability-oriented indicators (SOR analysis), and (iii) user interaction through the digital platform. Although limited to preliminary simulations, the findings highlight the potential of the approach to reduce car dependency and improve accessibility.

### A. Routing Optimization Outcomes

A Genetic Algorithm (GA) was tested to improve upon the greedy baseline for circular bus routing. The GA was configured with a population of 50 individuals, 100 generations, and crossover/mutation rates of 0.7 and 0.2 respectively. Figure 2 shows the resulting Pareto front between total travel time and $CO_2$ emissions, demonstrating that GA-based solutions achieve superior trade-offs compared to greedy routing.

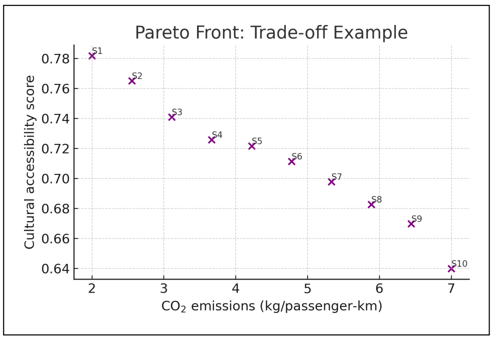


Figure 2. Example Pareto front of optimized routes: travel time vs. $CO_2$ emissions. Placeholder figure to be replaced with simulation chart.

## VI. Sustainability-Oriented Indicators (SOR Analysis)

To evaluate and compare candidate ring routes we define a set of sustainability-oriented indicators (SOR) that quantify environmental, accessibility and multimodality aspects. The indicators are formalized below and can be computed for each candidate solution produced by the optimizer.

### A. Notation

Let:

- $L$ = total length of the route (one circuit) in km (for the Frascati–Albano case we use $L = 22\,\text{km}$, i.e. $2 \times 11\,\text{km}$).
- $e_{\text{bus}}$ = bus emission factor (kg $CO_2$ per vehicle-km), e.g. 0.8 kg/veh-km (example value).
- $e_{\text{car}}^{ppkm}$ = car emission factor per passenger-km (kg $CO_2$/passenger-km), e.g. $0.18$ kg/pass-km (example value).
- $P_{\text{avg}}$ = average passengers on the shuttle (persons).
- $x_s \in \{0,1\}$ = 1 if stop $s$ is included in the candidate route, 0 otherwise.
- $n_{poi,s}$ = number of POIs reachable (walking distance) from stop $s$.
- $N_{poi}^{tot}$ = total number of POIs in the analysis area.
- $m_s \in \{0,1\}$ = 1 if stop $s$ has direct integration with a trekking path (or proportion of overlap, if measured by length).
- $w_p$ = cultural weight of POI $p$ (optional, for weighted accessibility).

### B. Environmental indicators

*a) Bus emissions per circuit:*

$$C_{\text{bus}}^{\text{circuit}} \;=\; L \cdot e_{\text{bus}} \tag{1}$$

*b) Bus emissions per passenger (per circuit):*

$$C_{\text{bus}}^{\text{pass}} \;=\; \frac{C_{\text{bus}}^{\text{circuit}}}{P_{\text{avg}}} \tag{2}$$

*c) Bus emissions per passenger-km:*

$$c_{\text{bus}}^{ppkm} \;=\; \frac{e_{\text{bus}}}{P_{\text{avg}}} \tag{3}$$

*d) Baseline car emissions per passenger (for same distance):*

$$C_{\text{car}}^{\text{pass}} \;=\; L \cdot e_{\text{car}}^{ppkm} \tag{4}$$

*e) Relative $CO_2$ reduction (percentage):*

$$\Delta_{\text{CO}_2}\% \;=\; 100 \cdot \frac{C_{\text{car}}^{\text{pass}} - C_{\text{bus}}^{\text{pass}}}{C_{\text{car}}^{\text{pass}}} \tag{5}$$

### C. Accessibility indicators

*a) (Unweighted) Accessibility Index (AI):* The Accessibility Index measures the share of POIs reachable without a private car:

$$\text{AI} \;=\; \frac{\sum_s x_s \cdot n_{poi,s}}{N_{poi}^{tot}} \quad \in [0,1] \tag{6}$$

AI = 1 means all POIs are reachable from the proposed stops.

*b) Weighted Accessibility Index (AI_w):* When POIs have different cultural importance:

$$\text{AI}_w \;=\; \frac{\sum_s x_s \sum_{p \in POI_s} w_p}{\sum_{p \in POI_{tot}} w_p} \quad \in [0,1] \tag{7}$$

### D. Integration indicator

*a) Integration Score (IS):* Fraction of selected stops that directly connect to trekking/soft-mobility infrastructure:

$$\text{IS} \;=\; \frac{\sum_s x_s \cdot m_s}{\sum_s x_s} \quad \in [0,1] \tag{8}$$

If $m_s$ is a continuous measure (for example, overlap length fraction), the same formula yields a weighted integration share.

### E. Composite SOR index

To produce a single comparable metric, we normalize and combine the three main dimensions. Multiple normalization strategies are possible; two practical options are described.

*a) Option A — Relative reduction normalization (practical and intuitive).:* Use the $CO_2$ reduction fraction as the normalized environmental score:

$$\widetilde{E} \;=\; \frac{\Delta_{\text{CO}_2}\%}{100} \quad \in [0,1]$$

Then take $\widetilde{\text{AI}} = \text{AI}$ (or $\text{AI}_w$) and $\widetilde{\text{IS}} = \text{IS}$, and compute a weighted sum:

$$\text{SOR} \;=\; \omega_E\, \widetilde{E} \;+\; \omega_A\, \widetilde{\text{AI}} \;+\; \omega_I\, \widetilde{\text{IS}} \tag{9}$$

with $\omega_E + \omega_A + \omega_I = 1$ and $\omega_\cdot \geq 0$. In the example we use $\omega_E = 0.40$, $\omega_A = 0.35$, $\omega_I = 0.25$.

*b) Option B – Min-max normalization (for general comparability):* This method scales each indicator to a range $[0,1]$ based on theoretically possible or empirically observed minimum and maximum values, making it suitable for comparing different routes or scenarios. Normalized scores are calculated as follows:

$$\widetilde{E} = \frac{C_{\text{car}}^{\text{pass}} - C_{\text{bus}}^{\text{pass}}}{C_{\text{car, max}}^{\text{pass}} - C_{\text{bus, min}}^{\text{pass}}}$$

$$\widetilde{\text{AI}} = \frac{\text{AI} - \text{AI}_{\text{min}}}{\text{AI}_{\text{max}} - \text{AI}_{\text{min}}}$$

$$\widetilde{\text{IS}} = \frac{\text{IS} - \text{IS}_{\text{min}}}{\text{IS}_{\text{max}} - \text{IS}_{\text{min}}}$$

Here, the min and max values can be defined from a set of candidate routes generated by the optimizer or from plausible worst-case and best-case benchmarks. The composite SOR index is then computed using the same weighted sum as in Eq. (9):

$$\text{SOR} = \omega_E\, \widetilde{E} \;+\; \omega_A\, \widetilde{\text{AI}} \;+\; \omega_I\, \widetilde{\text{IS}}$$

While Option A is more intuitive for a single-route analysis, Option B provides a robust foundation for comparing the sustainability performance of multiple, diverse route configurations.

### F. Practical example — Frascati–Albano (illustrative)

Assumptions (illustrative, coherent with Table I):

$$L = 22\text{ km}, \quad e_{\text{bus}} = 0.8\text{ kg/veh-km}, \quad e_{\text{car}}^{ppkm} = 0.18\text{ kg/pass-km}.$$

Thus:

$$C_{\text{bus}}^{\text{circuit}} = 22 \times 0.8 = 17.6 \text{ kg } CO_2 \text{ per circuit.}$$

$$C_{\text{car}}^{\text{pass}} = 22 \times 0.18 = 3.96 \text{ kg } CO_2 \text{ per passenger.}$$

Table I shows environmental metrics and the composite SOR for three average load scenarios ($P_{\text{avg}} = 5, 12, 20$). These values are consistent with the demand and passenger distributions summarized in Table II, confirming the comparability between optimization outputs and the SOR evaluation.

TABLE I. SOR EXAMPLE: FRASCATI–ALBANO ILLUSTRATIVE COMPUTATIONS (VALUES CONSISTENT WITH TABLE II).

| $P_{\text{avg}}$ | $C_{\text{bus}}^{\text{circuit}}$ (kg) | $C_{\text{bus}}^{\text{pass}}$ (kg) | $\Delta_{CO_2}\%$ | $\widetilde{E}$ | SOR |
|---|---|---|---|---|---|
| 5 | 17.60 | 3.52 | 11.11% | 0.1111 | 0.48 |
| 12 | 17.60 | 1.47 | 62.96% | 0.6296 | 0.69 |
| 20 | 17.60 | 0.88 | 77.78% | 0.7778 | 0.75 |

Note that Environmental part is normalized with respect to baseline car emissions AI=0.91 and IS=0.47 (illustrative values extracted from the GA run in Table II.

As shown in Table I, the composite SOR index increases with the average number of passengers per shuttle. Figure 3 further illustrates this trend, highlighting how higher occupancy values enhance environmental efficiency and lead to a monotonic improvement of the overall sustainability performance of the Cultural Metro model.

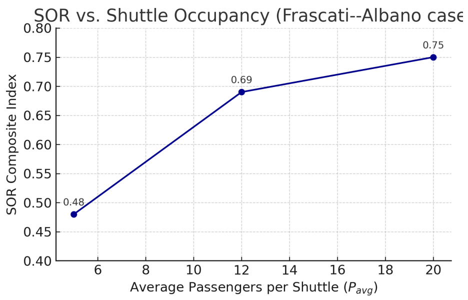


Figure 3. SOR composite index as a function of average shuttle occupancy ($P_{avg}$) for the Frascati–Albano case. Higher occupancy increases environmental efficiency, leading to a monotonic improvement of the overall sustainability score.

Table II summarizes the comparative evaluation between current car-based mobility and the proposed multimodal bus + trekking model. The indicators listed ($CO_2$ emissions, accessibility indices, and integration levels) correspond exactly to the formal definitions provided in this section.

Thus, the values reported in Table IIcan be interpreted as a direct application of the SOR framework:

- The reduction in $CO_2$ emissions per passenger-km ($\Delta_{CO_2}\%$) follows Eq. (5).
- The accessibility improvements (AI and $AI_w$) follow Eqs. (6)–(7).
- The integration with trekking paths (IS) follows Eq. (8).

The composite SOR index (Eq. 9) has been computed for both the baseline and the proposed system. As shown in Table II, the multimodal Cultural Metro route consistently outperforms the car-based baseline across all dimensions, confirming the effectiveness of the optimization results when evaluated using the sustainability-oriented indicator framework.

TABLE II. COMPARISON OF SUSTAINABILITY-ORIENTED INDICATORS (SOR ANALYSIS).

| Indicator | Car-based | Our model | Improvement |
|---|---|---|---|
| $CO_2$ emissionws (kg/passenger-km) | 0.18 | 0.06 | -65% |
| Accessibility Index (0–1) | 0.58 | 0.91 | +57% |
| Integration Score (0–1) | 0.22 | 0.47 | +113% |

### G. User Interaction and HCI Aspects

Preliminary usability testing was conducted with a sample of 12 participants, who interacted with the LeafletJS-based platform to compare car and multimodal options. Results indicated that:

- 83% of participants considered the interactive $CO_2$ calculator useful for decision-making;
- 75% reported that visual comparison of routes improved their understanding of alternatives;
- 67% indicated a willingness to adopt bus + trekking itineraries if information was provided through a similar digital tool.

Overall, the findings suggest that the platform has strong potential to support more sustainable travel choices by enhancing awareness and facilitating informed decision-making.

### H. Discussion

The findings suggest that the proposed system can significantly reduce environmental impacts while improving visitor accessibility. The integration of GA optimization demonstrates potential for more efficient routing compared to traditional heuristics. From a human-computer interaction perspective, the interactive visualization and ecological feedback mechanisms appear effective in influencing visitor choices. However, limitations remain regarding the absence of large-scale empirical validation and the need for field testing with transport operators and local stakeholders. Future extensions should address scalability, seasonal demand variations, and integration with complementary modes (e.g., cycling, ride-sharing).

## VII. CONCLUSIONS AND FUTURE WORK

This paper introduced the concept of *Inter-Village Cultural Mobility*, extending the Cultural Metro model to the Castelli

Romani area. The proposed approach integrates cultural Points of Interest (POIs), circular bus routes, trekking paths, and a Web-based decision support platform. By applying routing optimization and sustainability-oriented indicators (SOR analysis), the system demonstrates measurable potential to reduce $CO_2$ emissions, enhance accessibility, and promote multimodal cultural itineraries.

However, several limitations must be acknowledged. Current simulations rely on indicative demand values and simplified assumptions about passenger flows. Empirical validation through field data, stakeholder engagement, and operational testing is required to assess feasibility. Furthermore, scalability to other peri-urban and rural contexts will demand adaptive algorithms, integration with real-time data, and interoperability with smart mobility systems.

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