

Assessing and Explaining Road Network Performance in Data-scarce Contexts: The Case of the Constantine Metropolis in Eastern Algeria

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Abstract: Accurately assessing transport network performance in developing countries is a challenging task due to the lack of reliable data. This article proposes an operational approach to evaluate the performance of the road network using an accessibility-based method. It examines both the topological and economic dimensions of the network by applying graph theory and conducting a road traffic survey to assess temporal accessibility. In parallel, the analysis incorporates the urban structure and the spatial positioning of cities to explain variations in accessibility and network performance between off-peak and peak hours. The results reveal that Constantine's Road network has a radio-concentric structure that requires reconfiguration into a more reticular layout, in line with the increasingly polycentric form of the metropolis. These findings can support more informed urban planning decisions, which are essential for improving the daily transport services for both local and non-local users.

Keywords: Road network, transport, accessibility, mobility, performance

1. Introduction and Literature Review

Urban transport is a major challenge for contemporary cities, largely due to the mismatch between spatial expansion, population growth, and the slower development of road infrastructure [1]. Road networks are central to economic activity and daily mobility [2], and their performance can be defined across various thematic domains such as traffic fluidity, accessibility, maintenance, and safety, for which the scientific literature proposes various measurement indicators [3]. Recent studies highlight that the integration of resilience, equity, and sustainability dimensions is becoming essential in defining road network performance in metropolitan contexts [4,5].

The literature reveals a trend towards increasingly complex and disaggregated performance measures, which heightens the difficulty of calculation and interpretation for researchers and policymakers [6]. Existing studies generally focus on analyzing the structure and functioning of the

network based on topological, and metric indicators [7]. but such data-intensive methods are often costly and difficult to apply in data-scarce contexts, calling for more flexible approaches. Recent research therefore advocates hybrid methods combining traditional indicators with accessibility and spatial interaction measures [8,9]. Our study seeks to address this gap through a performance analysis approach that integrates the analysis of urban structure and the geographical positioning of cities to explain variations in accessibility and network performance between off-peak and peak hours.

Road network performance shapes urban mobility and constitutes a key development asset. Cities with poor accessibility risk losing centrality and attractiveness [10]. However, network extensions often prioritize expansion over systemic efficiency, altering topology and internal connectivity [11,12]. Such strategies may also degrade natural environments and exacerbate spatial inequalities [13,14]. The impacts of spatial planning and transport policies are often evaluated using accessibility measures, whose results can be effectively interpreted to guide operational action plans [6]. Previous research has argued that accessibility assessment based on urban structure provides a better understanding of residential mobility patterns and job competition [15]. It also offers economic indicators linked to transport-related benefits [16] and helps explain development disparities between cities within the same urban agglomeration, particularly with regard to urban sprawl [17]. Based on an empirical review of human settlement patterns, accessibility has been identified as a planning tool that influences and guides metropolitan area development, affecting location choices [6,18].

In Constantine, residential migration and peri-urban relocation policy have shifted population, activities, and services towards peripheral cities, generating new functional ties and complex mobility patterns that strain road infrastructure [19]. Yet, the road network remains radial-concentric, mismatched with the metropolitan strategy of fostering polycentricity. Comparable cases in other rapidly growing cities show that persistent radial patterns hinder polycentric development [20,21]. In Constantine's vehicle numbers rose from 2886 in 2000 to 37728 in 2020 [22], while road development lagged behind. A thorough evaluation of structural and functional performance is thus essential to guide metropolitan planning, an approach aligned with recent calls to integrate road capacity analysis with urban growth modelling in fast-motorizing cities [23].

In the face of rapid demographic growth and shifting urban centralities, Constantine's radial-concentric road network proves increasingly inadequate, generating accessibility and mobility imbalances, especially at peak hours. This study examines how urban development and the move toward a polycentric structure affect network performance, and what planning measures could mitigate these effects. By integrating territorial logics and urban dynamics into performance assessment, the findings highlight the interdependence among metropolitan cities and explain performance variations. On this basis, planning guidelines are proposed to improve both road and transport system performance.

2. Data and Methods

Accessibility reflects how easily individuals can reach destinations and serves as a cross-cutting indicator of both structural and functional road network performance. It captures the range of travel opportunities offered by the system, considering cost, time, comfort, and trip purpose [24]. In practice, the network is modelled as a graph nodes representing intersections and edges the connecting links then analyzed using graph theory tools [25]. Accessibility is closely tied to a place's distance from other activity centers, shaping its potential for attraction and diffusion and strongly influencing mobility patterns [11]. To evaluate the Constantine metropolitan road network, this study adopts a dual approach:

- First, graph theory was applied to construct a geographic accessibility matrix between the agglomeration's main cities. The SHIMBEL index was used for each city, it computes the sum of the lengths of the shortest paths to all other cities in the network in order to obtain "integral accessibility". This sum is then divided by the total number of cities in the network to derive "geographic accessibility" which allows for better comparability. A lower index value indicates good accessibility, whereas a higher index value reflects poor accessibility. This step assesses the relative positioning of urban canter within the existing road network and its spatial coverage, using also technical data on road, geometry, provided by the Directorate of Public Works (DTW), to generate the matrix of distance in kilometre's (Table 1).
- Second, a field survey was conducted to measure a real travel time and distance between the cities of the Constantine agglomeration, during both off-peak and peak hours. These observations highlight spatial and temporal variations in accessibility, enabling the identification of congestion zones requiring targeted interventions such as reinforcement, redevelopment, or functional reclassification of the network. The survey was conducted over one month of intensive fieldwork during November 2018, excluding public holidays and weekends in order to ensure that the measurements are representative of typical weekday mobility conditions experienced by the population.

For the traffic counts, a personal car equipped with a GPS device, a stopwatch, and the vehicle's trip odometer was used to directly measure both the kilometer distances and travel times between the cities of the agglomeration. In this case, all parameters influencing accessibility are automatically taken into account (traffic congestion, road conditions, individual behavior, traffic regulations, etc.), which adds greater credibility to our results. The survey concerns only travel by private car and do not include other modes of transportation. Examining private car accessibility does not substantially bias the conclusions, as it captures the truly prevailing mode of daily travel.

2.1 Empirical Approach

The analysis is based on the assumption that users possess optimal knowledge of the road network, allowing them to systematically choose the fastest route. The field survey enabled the generation of two distinct matrices. The selected peak (7:30–9:00) and off-peak (21:00–6:00) time windows were defined following a careful field observation of daily traffic flow fluctuations. These periods correspond to the main morning commuting peak and the lowest traffic demand interval. Additional checks were conducted by slightly shifting the boundaries of the selected intervals (± 30 minutes). The results showed only marginal variations in accessibility values and did not alter the main conclusions regarding network performance.

- **Matrix 1:** Off-peak accessibility (9:00 p.m. – 6:00 a.m.): a time period characterized by low traffic volumes. Travel times are mainly influenced by road surface conditions, the presence of speed bumps or roundabouts, road curvature and slope, as well as speed limits.
- **Matrix 2:** Peak-hour accessibility (7:30 a.m. – 9:00 a.m.): a period marked by high traffic intensity. Congestion phenomena then become the primary determinants of travel time.

Based on these matrices, three types of accessibility were calculated:

- **Off-Peak Accessibility:** measures the minimum travel time between each pair of urban centers, assuming smooth traffic conditions.
- **Outbound Accessibility (Peak Hours):** cumulative travel time from a given center to all others. This is calculated as the sum of the travel times recorded in the peak-hour time matrix.
- **Inbound Accessibility (Peak Hours):** total time required to reach a given center from the other urban poles during peak hours.

2.2 Study Area

The Constantine agglomeration constitutes the living area for a population exceeding one million inhabitants [22]. Due to the attractiveness of its metropolitan-level services and facilities, as well as its strategic position as a crossroads, it manages to capture a significant share of the flows of people and goods in the eastern region of the country. Owing to the number and importance of the roads that cross it. The agglomeration is crossed by several types of roads (see Fig.1) which constitute the primary network ensuring connectivity between its cities and neighboring wilayas. Provincial roads and communal roads constitute the secondary network, serving local circulation.

At Constantine, public transport provision relies mainly on state-run and private buses, as well as the tramway linking the city of Constantine to the new town of Ali Mendjeli. The dominant role of private car use (approximately 87% of trips) reflects not only modal preference but also a long-standing deficit in public transport supply and efficient intermodal solutions.

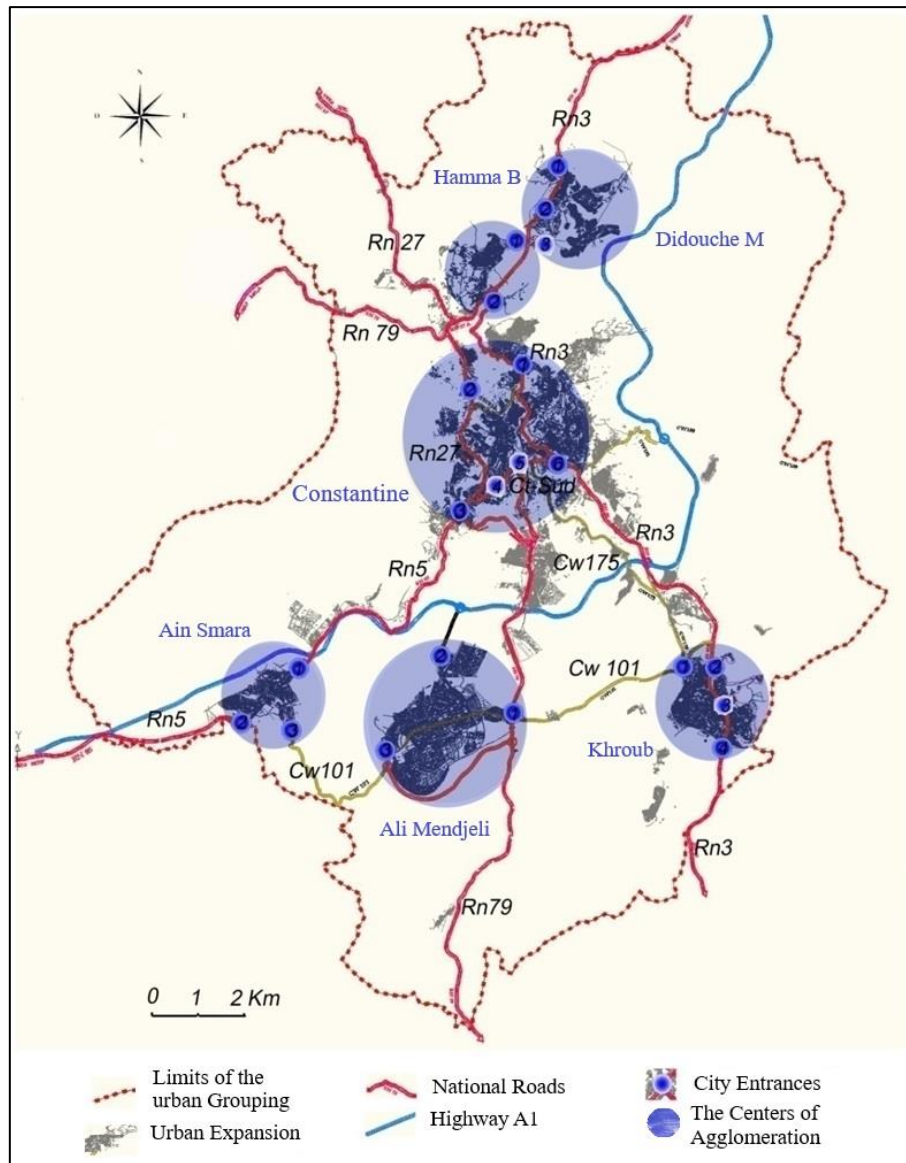


Fig. 1 The main road network of the Constantine agglomeration. Source: [19]

- **East–West Highway:** Crosses the Constantine agglomeration over a length of 50 km from east to west. Once fully completed, this highway will act as a bypass to alleviate road traffic pressure on the agglomeration's network, particularly on RN5, RN27, and RN3, which provide connections between the country's inland wilayas and the coastal wilayas. The highway has six exits within the agglomeration: two in the city of Constantine and four in the other cities it traverses.
- **National Roads (RN):** The national road network covering the agglomeration extends over 120 km, with dual carriageways (2x2 lanes). The roads forming this network are (RN3) connecting the north of agglomeration to Skikda and his south to Oum El Bouaghi. (RN5) leading to the wilaya of Sétif. (RN27) Coming from the wilaya of Jijel, passing through the municipalities of Hamma Bouziane and Constantine over 18.6 km and merges with (RN5). And finally (RN79) consists of two segments. The southern segment comes from the wilaya of Mila and joins (RN27) at Hamma Bouziane, while the northern segment comes from the wilayas of Batna, passes

through El Khroub and Constantine, and connects with the southern bypass linking (RN3), (RN5), and (RN27).

- **Wilaya Roads (CW) and Bypasses:** The connections between the agglomeration's centers especially those in the south are ensured by Wilaya roads (roads managed by the provincial authorities) and bypasses. The roads forming this network are CW101, CW175, the southern bypass of Constantine connecting RN3, RN79, RN5 and RN27, and the Massinissa bypass, connecting RN79 to RN5, passing through the Palma industrial zone.

3. Results and Discussion

3.1 Geographic Accessibility of the Cities

The first aspect related to the quality of service of the road network of the agglomeration concerns the positioning of cities within the road network. Based on the “kilometer-distance” indicator, the geographic centrality of each center within the Constantine agglomeration was calculated. The distances reported in the following table represent the shortest-path distances separating the entrances of the centers. The objective of this first accessibility assessment is to identify the mobility opportunities provided by the road network reduced to a graph representation.

Table 1 The kilometer-distance matrix of the road network of the Constantine metropolitan area.
Source: [19]

	Distance [km]	Destination						Accessibility	
		Constantine	Khroub	A.Mendjeli	Hamma	Didouche	Smara	Integral	Geographic
Departure	Constantine	-	13.1	14.1	6.3	12.1	14.9	60.5	12.1
	Khroub	13.1	-	10.3	22.3	26.9	23.4	96	19.2
	A-Mendjeli	14.1	10.3	-	22.1	27.6	11.7	85.8	17.16
	Hamma	6.3	22.3	22.1	-	4.8	22.1	77.6	15.52
	Didouche	12.1	26.9	27.6	4.8	-	27.7	99.1	19.82
	Smara	14.9	23.4	11.7	22.1	27.7	-	99.8	19.96

The results unsurprisingly highlight the strategic position occupied by Constantine relative to the other centers. On average, it is separated from the other centers of the agglomeration by only 12.1 km. The centers of Hamma and Ali Mendjeli subsequently emerge as the most geographically accessible. In contrast, Khroub, Didouche, and Ain Smara appear as the most peripheral centers within the agglomeration.

3.2 Temporal Accessibility of the Cities

The travel-time matrix connecting the cities during off-peak and peak hours is used to assess the network's capacity to accommodate travel flows under two different conditions, and consequently to measure how easily populations can move within the agglomeration.

Table 2 The temporal distance matrix connecting the centers of the agglomeration during off-peak hours. Source: [19]

Distance [min]		Destination						Accessibility	
		Constantine	Khroub	A.Mendjeli	Hamma	Didouche	Smara	Integral	Geographic
Departure	Constantine	-	14	13	10	12	15	64	12.8
	Khroub	14	-	7	25	27	21	94	18.8
	A-Mendjeli	13	7	-	24	26	10	80	16
	Hamma	10	25	24	-	2	18	79	15.8
	Didouche	12	27	26	2	-	20	87	17.4
	Smara	15	21	10	18	20	-	84	16.8

During off-peak periods, travel times within the Constantine agglomeration remain relatively short, with no city more than 20 minutes away from another (see table 2). This suggests a latent potential for polycentric development, provided that efficient public transport connections are established. Comparable findings have been reported in Mediterranean and African contexts, where compact travel times favor regional integration if supported by multimodal strategies[23,26].

By applying the SHIMBEL index, which measures accessibility as inversely proportional to the sum of distances to other nodes, Constantine unsurprisingly emerges as the most central node, while peripheral centers such as Didouche Mourad and Khroub show relatively higher travel times, consistent with experiences from other rapidly urbanizing metropolitan regions[27].

The situation changes dramatically during peak hours (see table 3). Accessibility deteriorates sharply across all centers, confirming the network's limited capacity to absorb commuting flows. Constantine is the most affected, with inbound accessibility decreasing, the average travel times rising from 12 to 35 minutes. Such steep reductions illustrate the vulnerability of monocentric networks, where congestion at a few gateways generates system-wide losses in accessibility. Similar asymmetries between inbound and outbound flows have been documented in metropolitan accessibility studies across Europe and the Middle East, highlighting the strong role of commuting patterns in shaping daily accessibility[28,29].

Table 3 The time distance matrix linking the agglomeration centers during peak hours (morning period). Source: [19]

Distance (Minute)		Destination						Outbound Accessibility	
		Constantine	Khroub	A.Mendjeli	Hamma	Didouche	Smara	Integral	Geographic
Departure	Constantine	-	24	21	16	19	24	104	20.8
	Khroub	35	-	11	62	65	23	196	39.2
	A-Mendjeli	42	9	-	54	57	16	178	35.6
	Hamma	19	43	44	-	3	40	149	29.8
	Didouche	40	46	49	5	-	43	183	36.6
	Smara	41	23	17	43	46	-	170	34
Inbound	Integral	177	145	142	180	190	146	-	-
	Geographic	35.4	29	28.4	36	38	29.5	-	-

[The matrix is not symmetric because the travel time between two centers is not the same in both directions].

3.3 Variation in Accessibility between Off-peak Hours and Peak Hours

The data presented in Table 4 (rows 1, 2, and 3) correspond to the integral temporal accessibility of the cities during off-peak and peak hours, derived from Tables 2 and 3. The data in rows 4 and 5 are obtained from the equation provided below the table, which measures the percentage change in accessibility. The negative result indicates that accessibility has decreased during peak hours compared to off-peak hours. The accessibility variation rate in [%] is computed according to the following formula :

$$\text{Variation rate} = \frac{\text{Accessibility Off Peak Hours} - \text{Accessibility Peak Hours}}{\text{Accessibility Off Peak Hours}} * 100 \quad [\%]$$

Inbound Accessibility: measures the minimum time required to reach a center from the other centers within the agglomeration.

Outbound Accessibility: measures the minimum time required to reach all centers of the agglomeration from a given center.

Table 4 Variation in accessibility of the centers of the Constantine agglomeration between off-peak and peak hours. Source: [19]

Overall Accessibility	Constantine	Khroub	A.Mendjeli	Hamma	Didouche	A.Smara
Accessibility/Off-Peak Hours [min]	64	94	80	79	87	84
Inbound Accessibility/Peak Hours [min]	177	145	142	180	190	146
Outbound Accessibility/Peak Hours [min]	104	196	178	149	183	170
Variation Rate/Inbound Accessibility (%)	-176%	-54%	-78%	-128%	-118%	-74%
Variation Rate/Outbound Accessibility(%)	-62%	-108%	-122%	-89%	-110%	-102%

All the cities are impacted by accessibility reducing, though to varying degrees. In addition to Constantine, which recorded a 176% decrease in accessibility, Hamma Bouziane and Didouche Mourad experience inbound accessibility reductions of 128% and 118% respectively, since access requires passing through congested Constantine gateways. In contrast, Ali Mendjeli, Khroub, and Smara show relatively lower reductions (between 54% and 78%), which can be explained by their peripheral positions and reliance on more fluid secondary road sections.

Interestingly, the pattern is reversed when analyzing outbound accessibility. Here, Constantine records the lowest reduction rate (62%), while peripheral centers show sharper declines, up to 122% in Ali Mendjeli. This asymmetry reflects daily commuting dynamics: morning traffic is strongly oriented toward Constantine, where jobs, services, and educational institutions are concentrated, whereas outbound flows remain comparatively smoother.

The spatial distribution of congestion points observed during peak hours is illustrated in the (figure 2). The map confirm that congestion is not evenly distributed but concentrates at Constantine's entrances, reinforcing the structural dependency of the entire agglomeration on its central city. This monocentric traffic pattern results in systemic vulnerabilities, where minor disruptions at Constantine's gateways generate disproportionate accessibility losses across the network.

From a planning perspective, these results highlight the urgent need to diversify transport supply and reduce reliance on private cars. The inclusion of multimodal accessibility is not only a handle for improving access to people but is also a weighted but crucial contribution in the overall efficiency quality of the road network. Experiences suggest that accessibility improvements are most effective when road projects are complemented by investments in public transport modes such as bus rapid transit (BRT), tramways, and intercity bus services[23]. Accessibility research stresses that improving mobility is not solely about reducing travel times but also about enhancing network resilience and integrating transport with land-use planning[29]. Without such integration, the agglomeration risks reinforcing structural vulnerabilities typical of car-dependent monocentric systems[30].

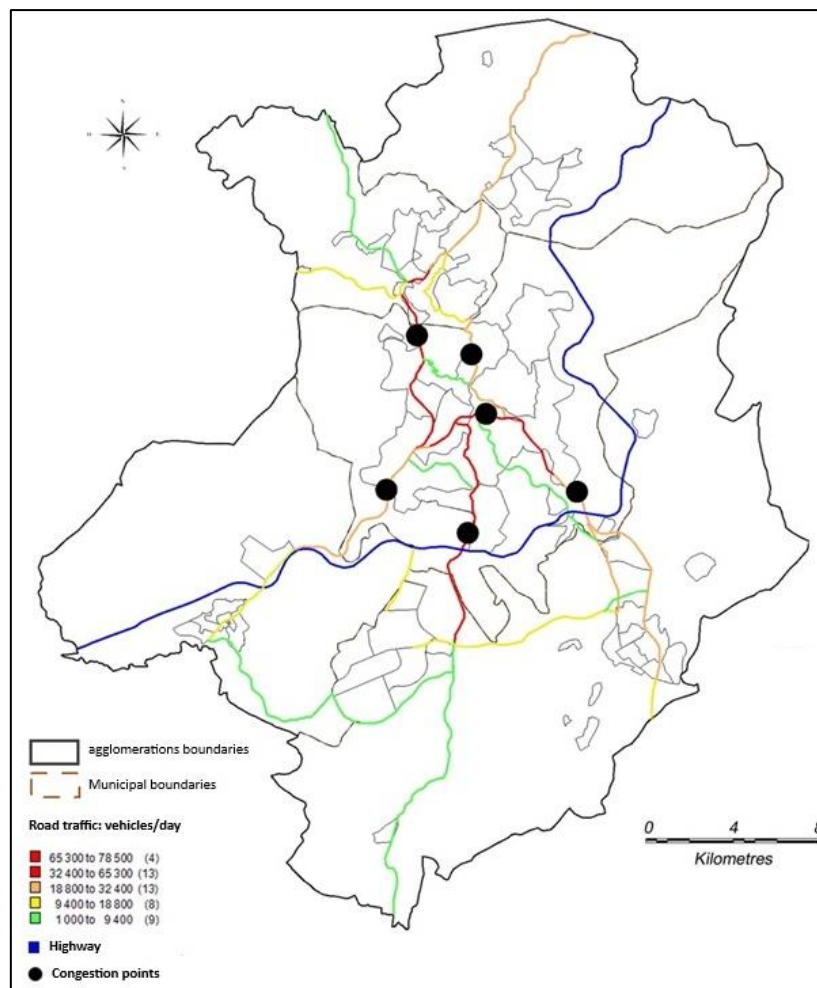


Fig. 2 Saturation level of the agglomeration's road network. Source: [19]

4. Conclusion

The accessibility-based method used in this paper is highly transferable to other data-scarce metropolitan regions, as it relies on simple indicators (distance and travel time) and on a network-based modelling approach that can be adapted to different morphological and socio-economic contexts. Local specificities (urban form, motorization level, mobility practices) can be incorporated through parameter calibration and time-window adjustments, without undermining the robustness of the methodological framework.

The results show that the configuration of the agglomeration's road network has not truly kept pace with urban development. Mobility patterns have become increasingly complex, requiring a road network better adapted to the agglomeration's polycentric urban development model.

During peak hours, the network is unable to absorb the vehicle flows, especially in the central part of the agglomeration, leading to congestion and a reduction in accessibility that can reach up to 176%. Addressing this issue calls for further research focused on a deeper understanding of residents' mobility practices, in order to measure travel demand and consequently anticipate the necessary upgrades to the road infrastructure. The growing use of private cars, despite the availability of public transport, has significantly worsened the situation in terms of road safety. This is an aspect that must be addressed as a priority in any strategy aimed at reducing road accidents.

The creation of efficient alternative modes (structural public transport, intermodality and feeding services) could contribute to unburdening the road system from potential pressure as well as to limiting systematic use of private cars, notably improve the accessibility of populations, and thus reactivate the functional efficiency of an existing network that already managed good spatial connections between metropolitan poles but is currently overloaded by automotive demands.

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