Time-Series Analysis of Road Network Expansion and Urbanization Trends in Ankara

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Abstract. This study uses historical OpenStreetMap data and geospatial network analysis to examine Ankara, Türkiye, road network growth from 2007 to 2025. Yearly highway snapshots are reconstructed to quantify total network length, annual expansion rates, highway-type composition, and directional growth patterns. Projecting all geometries into a metric coordinate system ensures precise length estimation, and spatial differencing between years identifies new roadway segments. The results indicate a non-linear expansion trajectory with distinct growth phases, including rapid development during the early-to-mid 2010s followed by more gradual expansion in later years. Residential and tertiary roadways have grown the most, showing urban and suburban connectivity demands contributed to expansion. Directional analysis reveals pronounced anisotropy, with dominant expansion toward the northeast and east, consistent with Ankara's major urban development corridors. To contextualize infrastructure growth, June-month Normalized Difference Built-up Index (NDBI)–based built-up ratios were extracted annually from Landsat imagery. While there is short-term correlation between highway expansion and built-up development during periods of rapid growth, this relationship does not persist over time, indicating that highway expansion in Ankara is primarily influenced by infrastructure-led planning rather than short-term urban densification. Future studies should use direction/corridor-specific built-up indicators to examine spatially varied urban responses to anisotropic highway growth.

1 Introduction

Transportation infrastructure is widely acknowledged to generate significant environmental costs [1], primarily through its role in driving land use and land cover (LULC) change. LULC encompasses the utilization of land, its resources, and the physical surface cover, including water bodies, vegetation, forests, agricultural land, and urban areas [2]. Changes in LULC are widely recognized as one of the most significant anthropogenic disturbances to the environment, leading to various microclimatic and ecological impacts [3]. Consistent with

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this, existing research suggests that road networks have a pronounced ecological influence over extensive portions of national territories, impacting about 15–20% of land in the United States, roughly 16% in the Netherlands, and nearly one-fifth of China, with these effects expected to escalate as an estimated 25 million km² of new roads are developed globally by 2050 [4,5]. In this context, understanding the temporal dynamics of land use/land cover (LULC) is essential for sustainable urban planning and effective natural resource management, as planning and transportation decisions, particularly road network expansion, directly influence land-use patterns and ultimately shape long-term urban sustainability, livability, and quality of life [6,7].

Within this context, Wey and Huang (2018) introduced a dynamic, data-driven framework for assessing transportation sustainability in livable cities. Treating the city as a time-dependent system, their research combined expert-based indicator selection with temporal data analysis to capture the changing nature of transportation sustainability. The methodology, which combined the Fuzzy Delphi Method with a Dynamic Network Process and time-series modeling, allowed for the assessment of changing indicator priorities and the development of sustainable and livable urban transportation strategies [8]. Extending this line of inquiry toward ecological outcomes, Zheng et al. (2021) examined how road networks affect urban eco-environmental quality across space by combining a remote-sensing-based ecological index (RSEI) with geographically weighted regression (GWR). Their results showed that higher road density—measured using kernel density of roads (KDR)—is generally linked to reduced vegetation cover, lower surface moisture, and poorer overall ecological conditions, while being associated with increased built-up areas, exposed bare soil, and higher land surface temperatures. The study also found that these impacts are stronger near river corridors and that vegetation-bare soil interactions explain road-related ecological effects' spatial variability [9]. Complementing these spatially explicit analyses, Nwaezeigwe et al. (2025) analyzed long-term urban infrastructure expansion in Osogbo, Nigeria (1987–2023), reporting a 133.45% increase in total infrastructure, driven largely by a 256.47% growth in road networks. This expansion coincided with a marked reduction in vegetation cover (67.81% to 29.08%) and increased bare ground, underscoring the environmental costs of rapid, infrastructure-led urbanization and the need for sustainable planning [10]. Lastly, Ramamoorthy et al. (2025) analyzed spatiotemporal urbanization in Hyderabad (2000–2020) using multi-temporal Landsat imagery and remote-sensing-based change detection. Spectral indices (NDBI, NDVI, NDWI) and raster-based density analyses revealed that road network expansion is a primary driver of urban sprawl, characterized by increasing built-up density and concurrent declines in vegetation and surface water, particularly along major transit corridors and metropolitan fringes [11].

Given the central role of road networks in urban land-use change, this study aims to examine the spatiotemporal relationship between highway expansion and urban growth in Ankara, Türkiye, as a metropolitan case study. Using a long-term highway network dataset (2007–2025) together with remotely sensed built-up land indicators, the study investigates (i) the dominant directions of highway expansion, (ii) changes in the pace of network growth over time, and (iii) the annual relationship between highway length and urban land development. By focusing on both temporal trends and directional patterns, the study seeks to clarify how highway expansion and urban growth interact over time. The main contribution of this work lies in its integrated and visually driven analysis, which combines directional expansion, annual change dynamics, and growth relationships to provide empirical insights into the influence of highway development on Ankara's urban expansion. The findings are expected to support data-informed approaches to sustainable transportation and urban planning.

2 Study area

The study area covers the administrative boundaries of Ankara, Türkiye. Ankara is one of the country's fastest-growing metropolitan regions, and its transportation infrastructure has expanded significantly in recent years. In this study, the road network within Ankara's provincial boundaries is considered the key spatial component for investigation. Fig. 1 shows the spatial distribution of the road network used for this study, including major and minor road segments throughout the study area.

Fig. 1. Ankara road segments in 2025 in QGIS view

3 Methodology

3.1 Highway network data acquisition and processing

Historical highway network data were obtained from Geofabrik [12], which provides time-stamped OpenStreetMap (OSM) extracts in Protocolbuffer Binary Format (.osm.pbf). These datasets represent widely used, versioned snapshots of the OSM database at specific points in time and are widely used in transportation and urban studies. A country-level extract for Türkiye was downloaded and used as the primary source for all highway network analyses.

Using the Osmium toolkit, yearly snapshots of the highway network were extracted for the period 2007–2025 [13]. For each target year, the corresponding Geofabrik extract was filtered to retain only features tagged with the OSM key: “highway = *” in Ankara province. The resulting road networks represent the cumulative state of the highway system at the end of each year. All road geometries were spatially clipped to the administrative boundary of Ankara Province to ensure spatial consistency across years.

For each yearly highway network snapshot, the following metrics were computed: Total highway length (km); year-to-year network expansion (Δ km); highway length by functional class, including residential, tertiary, secondary, trunk, and unclassified roads; directional highway expansion. To enable accurate metric length calculations, all geometries were reprojected to UTM Zone 36N (EPSG:32636).

3.2 Directional expansion and anisotropy analysis

To analyze the directional characteristics of highway expansion, a centroid-based anisotropy framework was applied. The geometric centroid of the highway network was computed for each year. Each road segment was assigned a representative point, and the bearing angle of this point relative to the network centroid was calculated. These bearing angles were discretized into eight directional sectors (N, NE, E, SE, S, SW, W, NW). Directional expansion was computed as the change in total highway length within each directional sector between consecutive years. This approach avoids topological overlay operations, which may introduce geometric artifacts, and ensures temporal stability in the estimation of directional growth.

3.3 Built-up area estimation using satellite imagery

Urban development was quantified using Landsat Collection 2 Level-2 Surface Reflectance imagery, including: Landsat 5 TM (2007–2011), Landsat 7 ETM+ (2012), Landsat 8 OLI (2013–2025). To minimize seasonal effects, only June imagery was used for all years [11]. This selection reduces the influence of vegetation phenology, snow cover, cloud cover, and low solar elevation angles, enabling consistent interannual comparison of built-up areas. Cloud-contaminated scenes were filtered using a cloud cover threshold of 40%, and annual median composites were generated for each year.

Built-up area estimation was performed using satellite imagery processed on the Google Earth Engine Code Editor platform [14]. Built-up areas were characterized using the Normalized Difference Built-up Index (NDBI), defined using short-wave infrared (SWIR) and near-infrared (NIR) values as:

$$NDBI=\frac{SWIR\text{-}NIR}{SWIR+NIR} \tag{1}$$

The Normalized Difference Built-up Index (NDBI) was originally proposed by Zha et al. (2003) [15] to automate the extraction of urban features by exploiting the high reflectance of built-up areas in the short-wave infrared spectrum. Sensor-specific spectral bands were used for each Landsat mission. Two annual indicators were derived: Mean NDBI represents average built-up intensity and built-up ratio defines as the proportion of pixels with NDBI > 0 within the study area.

3.4 Coupling analysis between highway expansion and urban growth

Highway network metrics and satellite-derived built-up indicators were integrated to analyze the relationship between transportation infrastructure development and urban growth. Our analytical framework consisted of three components. First, we assessed the correlation between total highway length and the built-up ratio. Second, we examined the longitudinal relationship between incremental highway expansion (Δ km) and year-over-year changes in built-up areas. Finally, we conducted a directional analysis to evaluate the spatial orientation of highway expansion in relation to urban development patterns. This multi-level analysis enables assessment of both long-term structural trends and short-term growth dynamics.

3.5 Implementation and Visualization

All data processing and analyses were conducted using Python, with the following tools: Osmium for OSM data filtering and extraction; GeoPandas and Shapely for spatial operations; Pandas and NumPy for data processing; Matplotlib for visualization. Results were visualized using time-series plots, bar charts, scatter plots, heatmaps, and polar diagrams to highlight temporal, structural, and directional patterns of highway expansion.

4 Results

This section presents spatiotemporal analyses of Ankara's highway network expansion (2007–2025) with urban growth and infrastructure-led development theory, using OpenStreetMap highways and satellite-derived urban indices to quantify expansion magnitude, spatial patterns, and underlying temporal drivers. Accordingly, Fig. 2 illustrates a sustained and substantial increase in the total length of Ankara's highway network throughout the study period, indicating long-term commitment to metropolitan-scale infrastructure development. From an infrastructure-driven urbanization perspective, transport networks shape future land-use patterns rather than simply responding to existing demand. The pronounced acceleration observed after 2013, particularly during the 2013–2015 period, suggests a phase of intensified state-led or policy-driven investment, consistent with theories of growth-oriented urban governance and large-scale capital accumulation in metropolitan regions. The pronounced interannual variability shown in Fig. 3, with peak expansion occurring in 2014, further supports the interpretation that highway development in Ankara is characterized by episodic growth bursts rather than smooth, incremental expansion. Such punctuated growth patterns align with political–economic models of infrastructure provision, where major expansion phases are often tied to strategic planning cycles, funding availability, or macroeconomic conditions, rather than continuous population or land-use change.

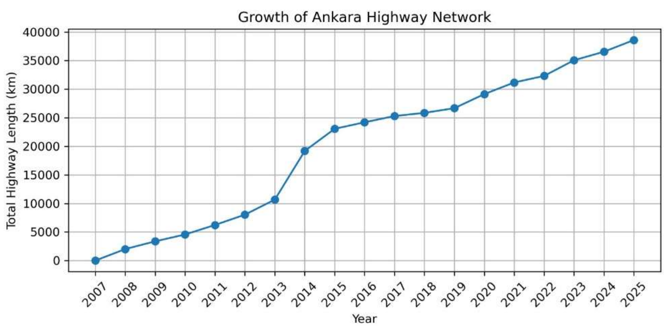

Fig. 2. Growth of Ankara highway network (2007–2025)

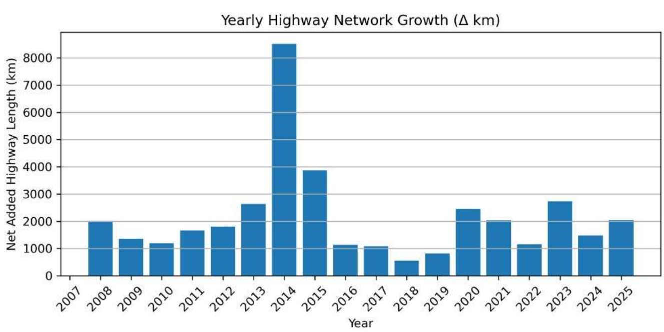

Fig. 3. Yearly highway network growth (Δ km)

Fig. 4 provides additional insight into the structural nature of this expansion by revealing that residential and tertiary roads account for the majority of network growth, particularly after 2013. This dominance suggests that highway expansion has primarily supported intra-urban accessibility and neighborhood-scale connectivity, rather than exclusively focusing on high-capacity intercity corridors. From an urban morphology perspective, this pattern reflects a shift toward polycentric and dispersed urban growth, where expanding residential zones require finer-grained road infrastructure to integrate new development areas into the

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metropolitan system. In contrast, the more moderate growth of secondary and trunk roads implies a relative stabilization of the primary arterial framework, consistent with mature metropolitan transport networks.

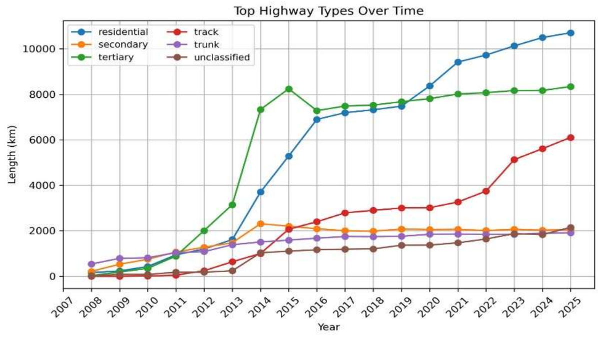
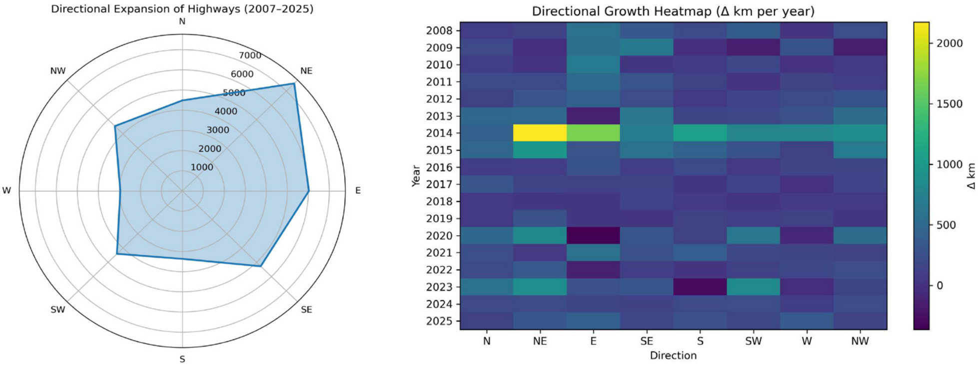


Fig. 4. Highway network growth by functional road class over time

Directional analysis in Fig. 5(a) highlights a clear spatial asymmetry in Ankara's highway expansion, with dominant growth toward the northeast (NE), followed by eastern (E) and southeastern (SE) sectors. This directional bias resonates with spatial development corridor theory, whereby infrastructure expansion tends to reinforce preferred growth axes shaped by topography, existing transport corridors, economic activity nodes, and planning priorities. Importantly, the heatmap analysis in Fig. 5(b) indicates that this directional dominance is largely driven by a limited number of high-intensity years, most notably around 2014, rather than by steady long-term accumulation. This finding suggests that Ankara's spatial expansion has been shaped by selective, high-impact interventions, rather than uniform radial growth.



(a) **(b)**

Fig. 5. Directional pattern of highway expansion: (a) cumulative growth by direction (2007–2025) and (b) annual directional growth visualized using a heatmap (Δ km)

Fig. 6 and Fig. 7 further contextualize highway expansion within broader urban development dynamics by comparing roadway growth with changes in the built-up ratio derived from NDBI. While total highway length increases steadily over time, built-up intensity exhibits considerable year-to-year variability. The occasional coincidence of rising highway length and increasing built-up ratio, such as in 2021, may reflect short-term coupling between infrastructure investment and urban development. However, the lack of consistent alignment across the study period challenges demand-driven transport models, which assume that infrastructure expansion closely follows urban growth.

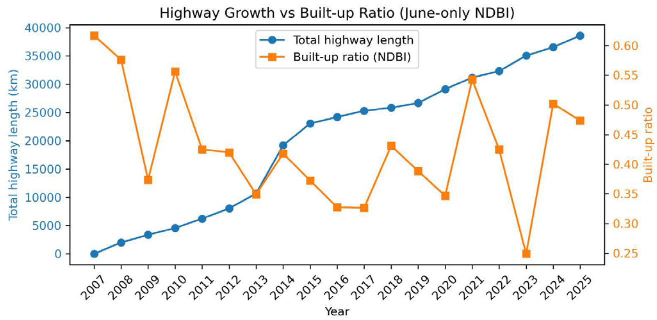


Fig. 6. Highway network growth and built-up area dynamics over time

In particular, Fig. 7(a) shows that some of the most substantial highway expansion phases occur when changes in built-up intensity are minimal or even negative, while **Fig. 7**(b) demonstrates that similar built-up ratios correspond to vastly different total highway lengths over the long term. Together, these findings support the interpretation that highway expansion in Ankara operates largely independently of short-term urban densification, aligning instead with theories of anticipatory infrastructure planning, where transport networks are constructed in advance of, or irrespective of, immediate land-use change.

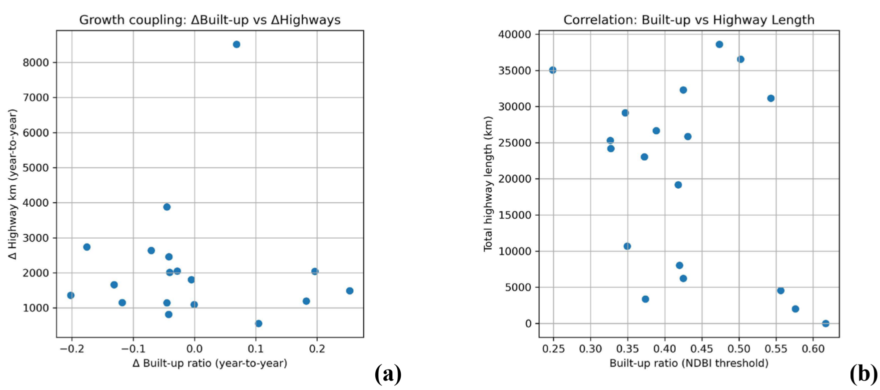


Fig. 7. Built-up ratio and highway expansion: (a) Short-term growth coupling and (b) Long-term correlation

Overall, the results suggest that Ankara's highway network expansion reflects a combination of strategic planning decisions, spatial development priorities, and episodic investment cycles, rather than a simple response to urban growth metrics. This decoupling between infrastructure expansion and built-up intensity underscores the importance of viewing transportation networks not merely as passive outcomes of urbanization, but as active agents shaping metropolitan form and future development trajectories.

5 Conclusion

This study shows that between 2007 and 2025, highway expansion in Ankara is steady but inconsistent, with growth mainly going northeast and eastward, while urban built-up development exhibits substantial year-to-year variability. Limited short-term alignment is observed between infrastructure expansion and urban growth, and growth-coupling and correlation analyses indicate that highway development is not consistently driven by concurrent urban land development. Instead, these findings support infrastructure-led urbanization theory, which conceptualizes transport networks as enabling structures that precede and shape urban development rather than merely responding to immediate demand. The results further show that corridor-based planning processes, rather than short-term changes in urban densification, exert a stronger influence on long-term highway expansion.

From a planning perspective, the short-term co-movement between residential and tertiary road expansion and rising NDBI around 2014 suggests that intensive highway investment phases may temporarily align with staged urban development. However, the lack of persistent alignment across the study period indicates that highway expansion in Ankara is primarily driven by infrastructure-led planning rather than short-term densification. These findings highlight the need for stronger coordination between corridor-based transport investments and land-use planning—particularly through zoning controls, density regulation, and transit-oriented development—to ensure that infrastructure provision supports compact and sustainable urban growth.

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