



Forest road network density and planning: Current status in Türkiye and global comparisons

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ABSTRACT

Review Article

Background and Aims Forest road networks are a prerequisite for sustainable forest management. Despite sustained investment since the 1960s, no continuous national series has distinguished between the road categories reported in Turkish official statistics. This study compiles such a series for 1998–2025, establishes which categories can defensibly be counted as network additions, and interprets the resulting density values against international benchmarks and harvesting system requirements.

Methods Official General Directorate of Forestry (GDF) statistics were compiled for 1998–2025,

covering the five road categories reported under the GDF construction program. Nominal road density was calculated as total road length divided by total forest area (m/ha). A targeted literature search in Web of Science, Scopus and TRDizin identified country-level density values for comparison.

Results Türkiye's classified forest road network expanded from 129,483 to 181,403 km between 1998 and 2025, and the total GDF-constructed network from 150,069 to 231,303 km. Nominal density rose from 7.30 to 9.90 m/ha between 1999 and 2025; including village and other public roads through forest, as last reported for 2022, gives 13.25 m/ha. Construction accelerated between 2019 and 2022, driven by tractor roads, whose cumulative length reached six times its 1998 baseline, before declining sharply. Across 24 countries, Türkiye fell below most Central and Alpine European countries (approximately 15–45 m/ha).

Conclusion Current density remains well below the twenty m/ha planning benchmark and international reference values. Closing this gap efficiently requires a shift from construction-focused approaches toward functional, optimization-driven network planning that accounts for terrain conditions and harvesting system requirements.

Key Words: Forest road density, forest road network, functional planning, global comparison, Türkiye

Orman yolu ağı yoğunluğu ve planlaması: Türkiye’de güncel durum ve küresel karşılaştırmalar

ÖZ

Giriş ve Hedefler Orman yol ağları, sürdürülebilir orman yönetiminin vazgeçilmez ön koşuludur. Türkiye’de 1960’lı yıllardan bu yana sürdürülen yol yapım yatırımlarına karşın, resmî istatistiklerde raporlanan yol kategorilerini birbirinden ayıran kesintisiz bir ulusal seri bulunmamaktadır. Bu çalışma, 1998–2025 dönemi için böyle bir seri derlemekte, hangi kategorilerin ağa yapılan ekleme olarak sayılabileceğini belirlemekte ve elde edilen yoğunluk değerlerini hem uluslararası referans değerlerle hem de ağın hizmet etmesi beklenen hasat sistemleriyle birlikte yorumlamaktadır.

Yöntemler Orman Genel Müdürlüğü’nün (OGM) 1998–2025 dönemine ait yıllık ormancılık istatistik bültenleri, OGM’nin yol yapım programında raporlanan beş yol kategorisi için derlenmiştir. İtbari yol yoğunluğu, toplam yol uzunluğunun toplam ormanlık alana oranı (m/ha) olarak hesaplanmıştır. Küresel karşılaştırma için Web of Science, Scopus ve TRDizin veri tabanlarında hedefli literatür taraması yapılmıştır.

Bulgular Türkiye’nin sınıflı orman yolu ağı 1998–2025 arasında 129.483 km’den 181.403 km’ye, OGM tarafından inşa edilen toplam ağ ise 150.069 km’den 231.303 km’ye ulaşmıştır. İtbari yoğunluk 1999–2025 arasında 7,30 m/ha’dan 9,90 m/ha’ya yükselmiştir; orman içinden geçen köy ve diğer kamu yolları dahil edildiğinde (2022 için yayımlanan son değer) bu oran 13,25 m/ha olmaktadır. İnşaat faaliyetleri 2019–2022 arasında hızlanmış, traktör yollarının kümülatif uzunluğu 1998 bazının altı katına ulaşmış, ardından hızla gerilemiştir. 24 ülkeli karşılaştırmada Türkiye, Orta ve Alp Avrupa ülkelerinin büyük bölümünün (yaklaşık 15–45 m/ha) gerisinde kalmıştır.

Sonuçlar Mevcut yoğunluk değeri, 20 m/ha’lık planlama ölçütünün ve uluslararası referans değerlerin önemli ölçüde altındadır. Bu açığın kapatılması, inşaat odaklı yaklaşımların ötesine geçen, arazi koşullarını ve hasat sistemi gereksinimlerini gözetten fonksiyonel ve optimizasyon temelli bir planlamayı gerektirmektedir.

Anahtar Kelimeler: Fonksiyonel planlama, küresel karşılaştırma, orman yolu ağı, orman yolu yoğunluğu, Türkiye

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1. Introduction

Forest roads are the backbone of any working forest management system. Without them, timber cannot move, fires cannot be fought, and silvicultural interventions cannot reach the stands that need them. Beyond timber, forest roads serve recreation, emergency access, biodiversity monitoring, and rural connectivity in many countries (Ring et al., 2024; Gümüş et al., 2008). The expanding scope of forest multifunctionality has, if anything, made road network adequacy more relevant, not less.

Forest roads are not unambiguously beneficial. Construction disrupts soil stability and hydrology, introduces edge effects that alter microclimate and species composition within the first 20–200 m of the road corridor, and creates barriers to wildlife movement that can compound habitat fragmentation at landscape scales (Eker et al., 2010; Cork et al., 2024). Road-associated sediment loading is among the most persistent negative legacies of forest operations, particularly on steep terrain (Dube et al., 2004). These trade-offs are well documented. What is less well documented, especially in countries with rapidly expanding networks, is whether road construction targets are being set and evaluated against functional criteria that account for ecological costs alongside operational benefits. Building roads to meet a kilometer target is not the same as building a network that works (Hruza, 2003; Kazama et al., 2021).

Forest road density, expressed as meters of road per hectare of forested area (m/ha), is the standard metric for assessing network adequacy and accessibility (Bayoğlu and Seçkin, 1982). Đuka et al. (2025) synthesized density data from across the globe and showed that values differ enormously by region: from around 2.4 m/ha in Russia to over 85 m/ha in Japan, with most Central European countries reporting values between 15 and 45 m/ha. Alpine countries such as Austria (approximately 45 m/ha) and Switzerland (~22 m/ha) are the product of decades of function-driven network planning, while Southeast European countries report more modest densities, typically between 7 and 20 m/ha (Đuka et al., 2025). In the Americas, optimal densities for eucalyptus plantations in Brazil have been estimated at approximately 30 m/ha under cost-minimization frameworks, though actual densities in natural forest management areas vary considerably (Simões et al., 2022; Morais et al., 2023). These figures matter because they provide the reference frame against which any national network, including Türkiye's, must be read.

Türkiye's forest road network has a complicated history. Before 1963, construction was largely reactive: roads were built to meet immediate operational needs, with slope and alignment standards frequently ignored (Aykut and Demir, 2005). Systematic planning began in 1964, and the GDF completed the first national road plan in 1974. Since then, construction has continued through successive planning periods, with the target road length revised repeatedly: from 144,425 km in the 1974 plan to 210,000 km in 2010, 281,000 km in 2013, 307,000 km in 2018, 380,466 km in 2021 and 365,215 km in 2022 (GDF, 2010–2022). Successive revisions reflected both expanded forest area and the progressive inclusion of village and other public roads usable for forestry operations. The network has grown substantially across all road categories since 1998, though the scale and trajectory of that growth are examined in detail in the results section of this study.

Despite this, studies evaluating Türkiye's forest road network at national scale and over a long statistical timeframe remain scarce. Most existing work has focused on technical and geometric standards (Hasdemir and Demir, 2000), examined road network structure within specific management units (Eker et al., 2010), or discussed functional planning criteria at a theoretical level (Demir, 2007; Gümüş et al., 2008). Bilici and Akay (2021) briefly addressed network development within a broader review of Turkish forestry operations, while Gümüş et al. (2019) offered one of the few national-scale assessments of forest road status and importance in Turkish forestry, based on data up to 2018. That study was a cross-sectional evaluation and did not capture the accelerating construction activity and density shifts of recent years. Đuka et al. (2025) recently placed Türkiye within a global overview of forest road density, drawing on case studies at planning-unit scale. What has not been available is a continuous national series disaggregated by road category, on which the definitional choices underlying the reported density values can be examined directly. A density of twenty meters of road per hectare is commonly used as a planning benchmark in Turkish forestry, yet the distance to that benchmark, measured against international values, has never been comprehensively examined.

This study uses official GDF statistics for 1998–2025 to document long-term development of Türkiye's forest road network across all road categories, and places Turkish forestry in an international context using comparative density data from the global literature. The data show sustained expansion over most of the study period, followed by a sharp decline after 2022. The argument here is not that Türkiye has failed; it is that the country now needs a different conversation: less about how many kilometers to build, and more about where, how to evaluate what already exists, and how to plan networks that serve ecological and social functions alongside timber access.

2. Material and Methods

2.1 Data sources for Türkiye

Data on forest road construction and network development in Türkiye were obtained from the annual forestry statistics bulletins published by the General Directorate of Forestry (GDF) for the period 1998–2025. These bulletins report on road work under two program groups: construction and maintenance. Five categories represent additions to the network and were included in this study: classified forest roads, fire safety roads, tower roads, tractor roads, and warehouse roads. They also report cumulative network totals and support infrastructure data, including pavement, maintenance, and bridge construction. Forest area figures used in density calculations were drawn from the same source. The hydraulic structures item reported in the same GDF table was excluded. GDF defines engineering structures as drainage systems, culverts, bridges and retaining walls constructed along an existing road alignment and reports them under the maintenance and repair program rather than the construction program. Their inclusion would double-count road length already reported under the construction categories. Survey, major repair, road superstructure and all maintenance items were excluded on the same basis. The network reported here therefore comprises the road categories constructed by the GDF and recorded in its annual statistics. Roads built by other public bodies that pass through forest and are

usable for forestry operations (village, public, mining and highland roads) are reported separately in GDF annual activity reports. These figures are available for 2010 and for 2013–2022, most recently 78,463 km for 2022; the basis was broadened in 2019 to include mining and highland roads, the same value (77,960 km) was reported unchanged for 2019, 2020 and 2021, and no figure has been published since 2022. Because a continuous and consistently defined series is not available for these roads, they are excluded from the longitudinal analysis presented in Section 3.2, which is based on the five GDF-constructed categories throughout. They are, however, included in the value used for international comparison in Section 3.3, since national totals reported in the comparative literature generally refer to all roads available for forest access. Both values are reported and labelled wherever they appear.

Road density was calculated as the ratio of total constructed road length to total forest area, expressed in meters per hectare (m/ha):

$$\text{Nominal Road Density (m/ha)} = \frac{\text{Total Forest Road Length (m)}}{\text{Total Forest Area (ha)}} \quad (1)$$

The density values reported in this study represent nominal road density, that is, the total road length divided by total forest area, and do not account for terrain characteristics, actual accessibility, or the spatial distribution of the network within the forest. Nominal density is a standardized, reproducible metric suited to longitudinal trend analysis and cross-country comparison, but it should not be read as a direct measure of forest accessibility. This distinction is taken up further in the results and discussion section, in the context of functional planning criteria. All raw data were compiled into a longitudinal dataset spanning 28 years, which allowed trend analysis across both construction activity and network-level density indicators. Forest area figures are published by the GDF only for inventory update years; density was therefore calculated for 14 years for which both road length and forest area data are available.

2.2 Literature search for global comparison

A targeted literature search was conducted to identify studies reporting quantitative forest road density values at country or regional scale. Three databases were searched: Web of Science, Scopus, and TRDizin. The search was performed using the following keyword combinations: "forest road density", "forest road network", "forest accessibility", and "orman yolu

yoğunluğu" (forest road density, for TRDizin). The search was limited to publications between 2000 and 2025. Studies were included if they reported a numerical road density value (m/ha) for a defined geographic unit (country, region, or management area) and were based on empirical data rather than modeling projections alone. Studies focused exclusively on road construction costs, geometric design standards, or harvesting technology without reporting density figures were excluded. Reference lists of retrieved articles were also checked to identify relevant older sources not captured by the database search. The final set of studies used for the global comparison is presented in the results and discussion section alongside the source information for each reported value.

3. Results and Discussion

3.1 Historical development of forest road construction in Türkiye

Forest road construction in Türkiye has passed through several distinct phases since systematic planning was established in the mid-1960s. Prior to 1963, roads were built without standardized criteria, producing networks that were poorly aligned, inadequately graded, and insufficient to open forest areas to operational use (Aykut and Demir, 2005; Bayoğlu and Seçkin, 1982). The GDF's first national road plan, completed in 1974 with a target of 144,425 km, formalized a shift toward planned construction. During this first planning period, approximately 3,500–4,000 km of forest roads were constructed annually (Gümüş et al., 2019). Construction was interrupted between 1984 and 1992 following the temporary closure of the Ministry of Forestry, though joint activities with the General Directorate of Rural Services partially compensated for the gap. By 1991, a cumulative total of 116,646 km had been built (Gümüş et al., 2019).

The data compiled for this study cover the period 1998–2025 and reveal two broadly different construction regimes (Appendix Tables A1 and A2). Between 1998 and approximately 2018, annual classified forest road construction remained relatively stable, averaging around 1,430 km per year with moderate year-to-year variation. From 2019 onwards, the pattern changed considerably (Figure 1). Annual construction of classified forest roads accelerated markedly, reaching a peak of 6,865 km in 2022 before declining to 2,158 km in 2024 and 2,510 km in 2025. This post-2018 acceleration appears in both the raw annual figures and the smoothed trend, ruling out a single exceptional year as the explanation.

Annual Forest Road Construction and 3-Year Moving Average, 1998–2025

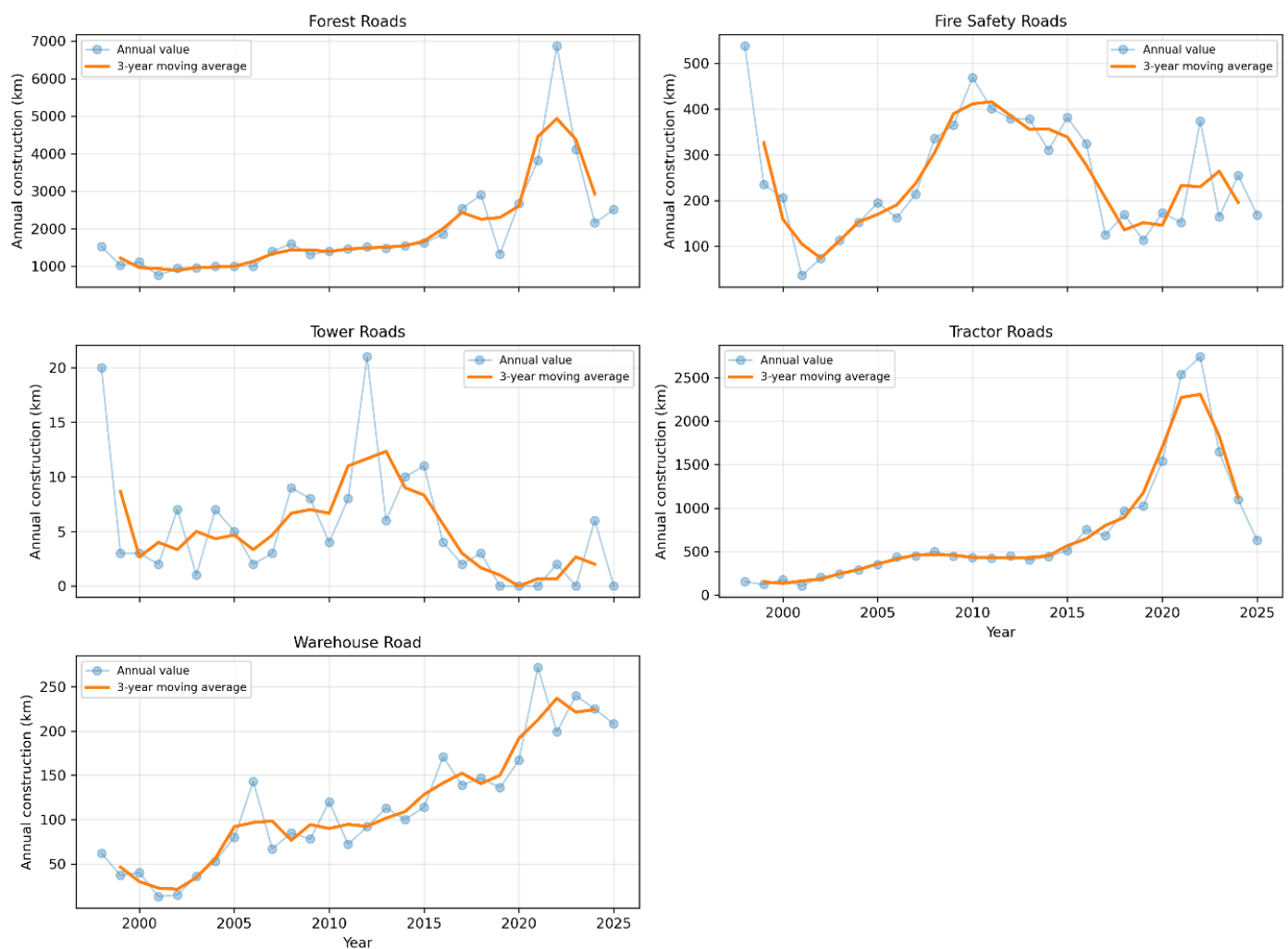


Figure 1. Annual forest road construction by road category in Türkiye, 1998–2025, with three-year moving average. Source: GDF (1998–2025)

The most striking trend in the construction data, however, concerns tractor roads. Between 1998 and 2018, annual tractor road construction averaged around 410 km per year and showed little directional trend. After 2018, construction in this category increased sharply, reaching 2,740 km in 2022, more than six times the pre-2018 average. Annual tractor road construction then fell sharply to 1,098 km in 2024 and 629 km in 2025. Indexed to the 1998 baseline, tractor roads had grown to six times their starting length by 2025, a trajectory far exceeding that of any other road category (Figure 2). Fire safety roads and tower roads showed comparatively modest growth throughout the study period, consistent with progressive saturation of the primary fire prevention network in accessible forest areas.

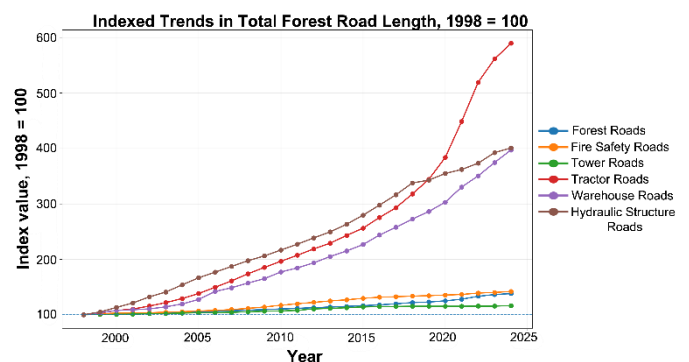


Figure 2. Indexed trends in total forest road length by road category in Türkiye, 1998–2025 (1998 = 100). Source: GDF (1998–2025)

The sharp rise in tractor road construction after 2018 is consistent with a broader policy reorientation toward mechanized harvesting operations, which depend more heavily on tractor-accessible terrain than on the classified road network (Gümüş et al., 2019). Tractor roads are generally built to lower geometric standards, are cheaper to construct, and can be deployed more

rapidly in steep or remote terrain where classified road construction would be prohibitively expensive. This expansion nonetheless raises questions the current planning framework is not well equipped to answer. Tractor roads are more susceptible to erosion and drainage failure than classified roads, and their rapid proliferation, without documented environmental impact assessment procedures, may generate cumulative ecological costs, although this has not been assessed here (Eker et al., 2010; Demir, 2007; Gümüş et al., 2008). The network's overall growth is clear and well-documented.

Road construction over this period tracked national roundwood production closely. Total production rose from 13.2 million m³ in 2000 to a peak of 31.9 million m³ in 2021, before falling to 26.8 million m³ in 2024 (GDF, 1998–2025). Annual construction of forest and tractor roads followed the same trajectory, averaging 1,878 km per year between 2000 and 2018 and 5,258 km per year between 2019 and 2024, with a correlation of $r = 0.84$ over 2000–2024. Both series peaked in 2021–2022 and declined together thereafter, which suggests that the post-2018

acceleration in road construction was associated with a parallel expansion in harvesting activity rather than with an independent infrastructure program.

3.2. Long-term trends in forest road density in Türkiye

Nominal forest road density in Türkiye increased from 7.30 m/ha in 1999 to 9.90 m/ha in 2025, representing a net gain of approximately 2.6 m/ha over 26 years (Table 1). The trend is consistent and uninterrupted, though the rate of increase has not been uniform. Between 1999 and 2015, density grew at a relatively modest pace, advancing from 7.30 to 8.19 m/ha over 16 years, an annualized rate of roughly 0.06 m/ha per year. After 2018, the pace accelerated noticeably, with density rising from 8.57 m/ha in 2018 to 9.90 m/ha in 2025, an annualized rate of approximately 0.19 m/ha per year, more than three times the rate of the earlier period. This pattern tracks the post-2018 surge in classified forest road and tractor road construction documented in Section 3.1.

Table 1. Total road length available for forestry activities, total forest area, and nominal road density in Türkiye, 1999–2025. Source: GDF (1998–2025)

Years	Total Roads (km)	Road rate of change (%)	Total Forest Areas (ha)	Stand rate of change (%)	Nominal Forest Road Density (m/ha)	Forest Road Density of Productive Forest Area (m/ha)	Density rate of change (%)
1999	151.493		20.763.248		7,3	15,11	
2005	159.678	5,4	21.188.747	2,05	7,54	15,03	3,29
2009	168.300	5,4	21.389.783	0,95	7,87	15,34	4,41
2010	170.724	1,44	21.537.091	0,69	7,93	15,24	0,75
2012	175.553	2,83	21.678.134	0,65	8,1	15,19	2,16
2015	182.980	4,23	22.342.935	3,07	8,19	14,4	1,13
2018	193.764	5,89	22.621.935	1,25	8,57	14,92	4,59
2019	196.362	1,34	22.740.297	0,52	8,63	15,01	0,81
2020	200.915	2,32	22.933.000	0,85	8,76	15,15	1,46
2021	207.699	3,38	23.110.000	0,77	8,99	15,39	2,58
2022	217.879	4,9	23.245.000	0,58	9,37	15,89	4,29
2023	224.046	2,83	23.363.071	0,51	9,59	16,34	2,31
2024	227.788	1,67	23.363.084	0	9,75	16,49	1,67
2025	231.303	1,54	23.375.331	0,05	9,9	16,65*	1,49

* Densities are calculated over total forest area from the five GDF-constructed road categories. Adding the 78,463 km of village, public, mining and highland roads passing through forest reported by the GDF for 2022 (the most recent year available) gives a 2025 total of 309,766 km and a density of 13.25 m/ha; this is the value used for international comparison in Table 2. Calculated over productive forest area only (13,892,213 ha in 2025), the corresponding 2025 value is 16.65 m/ha.

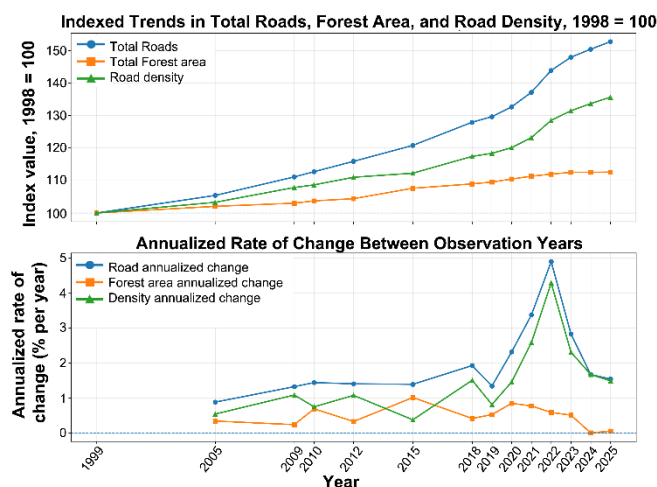


Figure 3. Indexed trends in total road length, total forest area and nominal road density (1999 = 100), and annualized rates of change between observation years, Türkiye, 1999–2025. Source: GDF (1998–2025)

Despite this progress, the gap between current density and the twenty meters of road per hectare commonly used as a planning benchmark in Turkish forestry remains substantial. This figure has a dual basis. GDF Communiqué No. 292 caps the total area of planned forest roads at 1% of the forest area, calculated as road length multiplied by the combined width of platform and ditch; for the standard B-type secondary road, whose platform and ditch together measure 5 m, this ceiling corresponds to approximately 20 m/ha (GDF, 2008). Hasdemir and Demir (2005) derive the same value independently as a planning norm for stands with a growing stock of 250 m³/ha or more, based on a road spacing of 500 m, with 10 m/ha applied to lower-stocking stands.

At the average rate of density increase recorded across the full study period (approximately 0.10 m/ha per year), reaching the twenty m/ha threshold would require approximately 100 additional years from the current baseline. Even at the accelerated post-2018 rate (approximately 0.19 m/ha per year), the target would not be reached until the 2070s. These projections assume no change in forest area, a simplification given that Türkiye's forest area has itself been expanding, which partially offsets road

construction gains in density terms (Table 1, Figure 3). Between 1999 and 2025, total forest area grew from 20.76 million hectares to 23.38 million hectares, meaning that some portion of the road network expansion was absorbed by the expanding denominator rather than showing up as density gains.

This distinction also matters when the network is compared to national planning targets, because the target itself has been redefined over time. The 1974 plan set a requirement of 144,425 km, revised to 201,810 km by the late 1990s, of which 133,693 km had been built by the end of 2004 (Hasdemir and Demir, 2005); both figures referred to roads constructed by the GDF. The target subsequently rose from 210,000 km in 2010 to 281,000 km in 2013, 307,000 km in 2018 and 380,466 km in 2021, before being set at 365,215 km in 2022 and 367,000 km in the 2024–2028 Strategic Plan (GDF, 2010–2022). Successive revisions reflected both the expansion of the forest estate and the progressive incorporation of village and other public roads usable for forestry operations (Gümüş et al., 2019). On the broader basis, which corresponds to that of the current target, the 2025 network of 309,766 km represents approximately 84% of the 367,000 km requirement.

The density values reported here are nominal: they describe the ratio of total road length to total forest area at national scale and say nothing about how that road length is spatially distributed, whether it is concentrated in accessible lowland areas or extended into remote and steep terrain, or whether individual stands fall within economically viable skidding distance of the nearest road. A forest management unit reporting 10 m/ha may have excellent accessibility in its production zones and effectively zero coverage in its protection forests, or the reverse. Demir (2007) noted this limitation explicitly in the Turkish context, arguing that road spacing and skidding distance, rather than aggregate density, are the operationally relevant metrics for evaluating network adequacy. Gümüş et al. (2008) similarly emphasized that functional planning criteria, specifically those accounting for harvesting system, terrain class, and ecological sensitivity, are needed alongside density figures to make meaningful management decisions. The national-scale density trend documented here is a necessary baseline, but it is not sufficient on its own to assess whether Türkiye's forest road network is meeting its management objectives. That question requires spatially explicit analysis at the planning unit level, which lies beyond the scope of this review.

3.3 Global comparison of forest road density and Türkiye's position

Forest road density varies enormously across the globe, and Türkiye's position in that range is worth examining carefully. Table 2 brings together density values from 24 countries and regions across Europe, Asia, and the Americas, drawn from the targeted literature search described in Section 2.2. The range runs from approximately 2.4 m/ha in Russia, where vast boreal forests remain largely roadless and timber is often extracted through seasonal ice roads, to over 85 m/ha in Japan, where decades of intensive plantation management and deliberate national investment have produced one of the densest forest road networks in the world (Havimo et al., 2017; Kaneko et al., 2024). Türkiye, at 13.25 m/ha in 2025 on the basis used in Table 2, sits in the middle of the Southeast European group.

Within Europe, the contrast between Alpine and Southeast European countries is particularly pronounced. Austria leads the European sample at an overall average of approximately 45 m/ha, though values vary considerably by ownership type, from 33.27 m/ha in federal forests to 49.1 m/ha in small private forests under 200 ha (Ghaffarian et al., 2009). France and Germany, two of Europe's largest forestry nations, report densities of 30–40 m/ha and 30–50 m/ha respectively, values that remain below their own optimal targets (Piekutin et al., 2015). Slovenia, at 24.8 m/ha, and Switzerland, at approximately 22 m/ha, similarly reflect decades of function-driven network planning, though Switzerland's national average masks substantial spatial variation from near zero in protected alpine zones to over 80 m/ha in intensively managed lowland forests (Krč and Beguš, 2013; Fraefel et al., 2021). Southeast European countries report values broadly comparable to Türkiye: Croatia between 7.63 and 15.64 m/ha depending on terrain category, Serbia at approximately 13.37 m/ha, Greece at 14.05 m/ha, and Bosnia-Herzegovina between 9.6 and 16.0 m/ha (Pentek et al., 2014; Bajrić et al., 2022; Liampas et al., 2019). Romania stands out as the lowest in the European sample at approximately 6.5 m/ha, a figure explained by both the fragmentation of forest ownership and chronically underfunded infrastructure investment (Hapa et al., 2023). Bulgaria, at approximately 7.9 m/ha, reflects similar constraints of limited infrastructure investment (Stoilov et al., 2014). Poland, at a national average of 15.28 m/ha with considerable regional variation, occupies an intermediate position (Grajewski, 2022).

Table 2. Nominal forest road density in selected countries across Europe, Asia, and the Americas (m/ha). Türkiye value calculated from GDF (1998–2025) data

Region	Country	Forest area (1000 ha)*	Forest Road Density (m/ha)	Source
Western Asia	Türkiye	22.532	13.25**	GDF (1998–2025)
Central & Eastern Europe	Poland	9.507	15.28	Grajewski (2022)
Central & Eastern Europe	Slovakia	1.926	~148	Sačkov & Barka (2023)
Central & Eastern Europe	Russia	815.312	~2.4	Havimo et al. (2017)
Central & Eastern Europe	Ukraine	9.702	7.8 – 10.1	Styranivsky et al. (2011)
Central & Eastern Europe	Czechia	2.681	18.0	Žáček and Klč (2008)
Central Europe	Germany	11.419	30 - 50	Piekutin et al. (2015)
South-West Europe	Italy	9.674	15.8 - 19.2 (truck-accessible)	Picchio et al. (2018)
South-West Europe	Spain	18.581	17.60	Pascual et al. (2018)
South-West Europe	France	17.420	30 - 40	Piekutin et al. (2015)
South-East Europe	Croatia	1.944	7.63 - 15.64	Pentek et al. (2014)
South-East Europe	Bosnia-Herzegovina	2.188	9.6 - 16.0	Bajrić et al. (2022)
South-East Europe	Serbia	2.723	~13.37	Srbijašume (2021)
South-East Europe	Romania	6.929	~6.5	Hapa et al. (2023)
South-East Europe	Bulgaria	3.919	~7.9	Stoilov et al. (2014)
South-East Europe	N. Macedonia	1.001	13.43	Trajanov et al. (2015)
South-East Europe	Greece	3.902	14.05	Liampas et al. (2019)
Alpine Europe	Switzerland	1.276	~22	Fraefel et al. (2021)
Alpine Europe	Slovenia	1.234	24.8	Krč & Beguš (2013)
Alpine Europe	Austria	3.895	45 (range: 33.27 - 49.1)	Ghaffarian et al. (2009)
Eastern Asia	Japan	24.935	~85	Kaneko et al. (2024)
Eastern Asia	China	223.737	12.94	Zhang et al. (2020)
Western Asia	Iran (Hyrcanian)	10.776	1 – 2	Jourgholami et al. (2013)
Americas	Brazil (Amazon)	494.196	17.48 – 22.51	Morais et al. (2023)

*Forest area figures are given for context only and are drawn from a single source (FAO, via World Bank, 2022) to ensure comparability across countries; they are not the denominators used in the density values reported in the third column, which are taken from the sources listed.

**The value for Türkiye includes both GDF-constructed road categories (231,303 km in 2025) and village, public, mining and highland roads passing through forest (78,463 km, as last reported for 2022). It could not be established from the source publications whether the values reported for other countries include comparable roads.

Slovakia's reported figure of approximately 148 m/ha warrants separate comment. This value stems from a measurement methodology that includes all secondary and tertiary access routes within forest management units, making direct comparison with countries using narrower road classification systems, including Türkiye, problematic (Sačkov and Barka, 2023). This is a recurring challenge in cross-country density comparisons: what counts as a forest road differs considerably across national classification systems, and nominal density figures capture those definitional choices as much as they capture actual network extent. Türkiye's figure of 13.25 m/ha covers the five road categories reported under the GDF construction program together with village, public, mining and highland roads passing through forest. The definitional sensitivity is substantial: the five construction categories alone give 9.90 m/ha, and the classified forest road network alone gives 7.76 m/ha. A threefold range of defensible values for a single country in a single year illustrates why nominal density figures from different sources should be treated as indicative rather than strictly comparable. Nominal density figures are also sensitive to whether public and rural roads passing through forest areas are counted. Türkiye's value here includes such roads; for most of the countries in Table 2 it was not possible to establish from the source publications whether comparable roads are included. This is a recurring limitation in cross-country density comparisons (Đuka et al., 2025), and one reason why the values in Table 2 should be read as indicative rather than strictly commensurable. Values for several countries in the sample derive from single national studies: Ukraine at 7.8–10.1 m/ha (Styranivsky et al., 2011), Czechia at 18.0 m/ha (Žáček and Klč, 2008), Spain at 17.60 m/ha (Pascual et al., 2018), North

Macedonia at 13.43 m/ha (Trajanov et al., 2015) and Serbia at approximately 13.37 m/ha (Srbijašume, 2021), the last of these an institutional monograph rather than a peer-reviewed source. Readers should bear these caveats in mind when interpreting Table 2.

Reported values are also sensitive to the reference year, which differs across sources by up to fifteen years, over which national networks have continued to expand. Together with the ownership and terrain effects noted above, this means nominal density values should be read as country-level approximations rather than precise, directly comparable measurements.

In Asia, the contrast between Japan and China is stark. Japan's density of approximately 85 m/ha is the product of a sustained national program of forest road investment stretching back several decades, driven by the need to harvest maturing plantation resources across steep and complex terrain (Kaneko et al., 2024). China, at 12.94 m/ha, is closer to Türkiye's current position but has set an ambitious national target of 17.5 m/ha as part of its national sustainable forestry program (Zhang et al., 2020). In contrast, the Hyrcanian forests of Iran report current road densities of only 1–2 m/ha, among the lowest values in the global sample, reflecting both challenging mountainous terrain and historically limited investment in forest road infrastructure (Jourgholami et al., 2013). A proposed target of 20 meters of road per hectare of forest area for the same region underscores the scale of the accessibility gap in parts of Western Asia. In the Americas, Brazil presents a heterogeneous picture: densities in Amazon concession areas range from 17.48 to 22.51 m/ha under current management regimes, while optimization studies for eucalyptus plantations suggest cost-minimizing densities of

approximately 30 m/ha under intensive harvesting scenarios (Morais et al., 2023; Simões et al., 2022).

Türkiye's current density of 13.25 m/ha is neither anomalously low nor close to adequate for a country with Türkiye's forest area, terrain diversity, and management intensity. It sits within the Southeast European group, above China (12.94 m/ha) and just below Serbia (13.37 m/ha) and North Macedonia (13.43 m/ha), but well below Poland (15.28 m/ha), the Alpine countries, France, Germany and Japan. The twenty m/ha benchmark is attainable in principle, since France, Germany and several other European countries report higher densities, but not on the current trajectory. Reaching it will require not only continued construction investment but also a shift in planning philosophy. Building more roads will raise the density figure; building the right roads in the right places will determine whether that figure translates into genuinely improved forest accessibility and management outcomes (Hruza, 2003; Gümüş et al., 2008; Tampekis, 2025).

3.4. From nominal density to functional planning: Implications for Türkiye

Türkiye has built a substantial forest road network over the past quarter-century, but at 13.25 m/ha on a comparable basis, or 9.90 m/ha counting only GDF-constructed categories, it remains below the values reported for countries where function-driven planning has been established for decades. The twenty m/ha benchmark is a reasonable long-term reference, but the current trajectory does not point toward it.

What the data cannot tell, and what no national-scale density figure can tell, is whether the roads being built are in the right places, serving the right functions, and being planned with adequate attention to ecological and social costs. This is the core limitation of nominal density as a planning metric, and it raises a more fundamental question about the current approach to forest road planning in Türkiye.

Forest road planning has traditionally been treated, in Türkiye as in many countries, as primarily a civil engineering problem: determine the required road length, identify a feasible route, and build to geometric standards. This is increasingly inadequate where forests are expected to deliver carbon storage, biodiversity conservation, watershed protection and fire resilience alongside timber, and where the ecological costs of road construction are better understood than a generation ago (Demir, 2007; Gümüş et al., 2008; Cork et al., 2024). Functional planning instead requires that networks be evaluated against the full set of objectives they serve rather than against a single density target (Hruza, 2003; Lugo and Gucinski, 2000): road spacing calibrated to the harvesting systems used in each terrain class (Demir, 2007; Seçkin, 1984); environmental impact assessment integrated into route selection from the outset (Gümüş et al., 2008); fire prevention geometry, wildlife corridors and slope stability considered alongside extraction efficiency (Bilici, 2009; Eker et al., 2010); and existing roads evaluated for condition and seasonal accessibility before new construction is prioritized (Gümüş, 2009).

The tools for this kind of planning are available and well-tested. GIS-based optimization frameworks, combined with digital elevation models and terrain analysis, allow planners to evaluate multiple road network configurations simultaneously

against economic, ecological, and social criteria (Picchio et al., 2018; Kaneko et al., 2024). Multi-criteria evaluation approaches have been applied in Greece (Tampekis, 2025) and Croatia (Pentek et al., 2014) to identify network configurations that minimize lifecycle costs while maintaining acceptable environmental performance. In Switzerland, spatially explicit road suitability assessments have been used to differentiate between areas where existing roads are adequate for timber hauling and areas where investment in network improvement or extension would yield the greatest accessibility gains (Fraefel et al., 2021). These approaches are not out of reach for Turkish forestry institutions: GIS-based road network evaluations have already been demonstrated at the planning unit level in Türkiye (Acar et al., 2017; Çalışkan and Karahalil, 2017) but have not yet been systematically integrated into the national road network planning process (Demir, 2007; Gümüş et al., 2008).

The tractor road expansion documented in Section 3.1 illustrates what happens in the absence of this kind of integrated planning. Tractor roads are built quickly and cheaply, they can access terrain that classified roads cannot reach, and they contribute to nominal density figures. But they are also the road category most susceptible to erosion, drainage failure, and slope instability, and their construction rarely involves the same level of route evaluation that classified roads require (Eker et al., 2010; Çalışkan and Çağlar, 2010). Annual tractor road construction almost tripled between 2018 and 2022, from 969 to 2,740 km, before falling back to 629 km by 2025. This expansion is likely to have improved operational access in some areas. Whether it has done so efficiently, sustainably, and without disproportionate ecological cost is a question the current planning and monitoring framework cannot answer. Establishing a systematic evaluation protocol for tractor roads, one that tracks not only kilometers built but sediment generation, drainage performance, and integration with the broader classified network, would be a concrete step toward more functional planning practice. The parallel movement of road construction and roundwood production documented in Section 3.1 is consistent with a network expanding in response to short-term harvesting demand rather than to a long-term accessibility plan, a pattern also reported for other countries where road investment follows production cycles (Kazama et al., 2021).

Türkiye would benefit from developing a national forest road evaluation framework that goes beyond the geometric standards currently used by the GDF and incorporates functional, ecological, and social criteria into periodic network assessment (Gümüş, 2009; Demir, 2007). Several European countries have moved in this direction, either through formal road assessment programs or through integration of road network evaluation into national forest inventory cycles. Such a framework would not replace the density benchmark: twenty meters per hectare remains a useful planning horizon. It would complement that target by ensuring that the roads being built to reach it are adding genuine functional value rather than simply adding kilometers.

3.5 Harvesting systems and road density requirements: A functional perspective

Nominal road density figures are not self-interpreting. The same value of 15 m/ha may represent an adequate network in a forest managed with cable extraction systems and an entirely inadequate one where forwarder-based harvesting is the norm. Different extraction technologies impose fundamentally different constraints on the maximum economically viable distance between a harvesting site and the nearest road. For forwarder-based cut-to-length (CTL) systems, in which a harvester processes trees at the stump and a forwarder transports logs to the roadside, productivity declines significantly with extraction distance beyond approximately 300–400 m, making dense road networks a functional prerequisite (Engler et al., 2024; Ghaffarian et al., 2009). Cable yarder systems can operate over considerably longer extraction distances than forwarders, reducing their road proximity requirement (Engler et al., 2024). Interpreting density figures without reference to the harvesting systems they are designed to serve can therefore produce misleading comparisons.

Across the 24 countries and regions included in Table 2, dominant harvesting systems vary substantially by region and fall into three broad patterns. The first covers countries where CTL systems account for most of the harvesting activity. In Germany, France, Italy, and Spain, CTL represents approximately 65%, 55%, 60%, and 60% of annual harvests respectively, and the forwarder is the modal extraction machine across Western and Central Europe (Bolding et al., 2025). The density values reported for Germany (30–50 m/ha), France (30–40 m/ha), and Poland (15.28 m/ha) are broadly consistent with the spatial requirements of ground-based mechanized extraction. Across the continental European biogeographical zone, harvester-forwarder systems account for approximately 72% of harvesting activity (Engler et al., 2024).

The second pattern covers Alpine countries where cable yarder systems play a significant role alongside ground-based machinery. In Austria, Switzerland, and Slovenia, steep terrain limits the operating range of conventional forwarders: approximately 35% of Swiss forest area is harvested with tower yarder systems, and winch-assisted harvester-forwarder combinations cover a further 30% in Austria and Slovakia (Pucher et al., 2023). These countries nonetheless maintain high road densities, because cable operations require developed networks at both ends of the yarding corridor and ground-based operations still dominate on accessible terrain. Japan presents a comparable case: despite relying on swing yarders and cable systems on its steep mountainous terrain, the country has invested heavily in access roads to maximize the proportion of its plantation resource that can be reached efficiently, resulting in a national density of approximately 85 m/ha (Kaneko et al., 2024).

The third pattern, covering Southeast European countries including Croatia, Bosnia-Herzegovina, Serbia, Romania, Bulgaria, North Macedonia, and Greece, is characterized by chainsaw felling combined with skidder or agricultural tractor extraction. Across the Mediterranean biogeographical region, chainsaw-skidder systems account for approximately 70% of harvesting operations, with harvesters and forwarders playing a limited role (Engler et al., 2024; Moskalik et al., 2017). The

density values reported for this group, typically between 6.5 and 16 m/ha, reflect both the lower road requirements of tractor and skidder extraction and the historically limited infrastructure investment in the region.

Türkiye sits between these groups. Primary timber extraction relies on a combination of chainsaw felling, farm tractor skidding, and cable systems deployed selectively on steep terrain (Bilici and Akay, 2021). This mixed system does not, in principle, impose the same road density requirements as a fully CTL-based operation. However, the expansion of tractor roads documented in Section 3.1 suggests a shift toward shorter extraction distances and higher road dependency, since tractor skidding is economically constrained to operate within a few hundred meters of a road, although annual construction in this category has fallen sharply since 2022. If this trajectory continues without accompanying network planning, the result may be a growing stock of access infrastructure that is costly to maintain, ecologically disruptive, and poorly integrated with the classified road system. Aligning road network investment with a clear, terrain-differentiated harvesting system strategy would allow Türkiye to use its road density targets more efficiently, concentrating higher-density networks where tractor-based operations dominate and accepting lower densities where cable systems can viably substitute.

4. Conclusion

By most measures, Türkiye's forest road network has grown substantially over the past quarter-century. From 129,483 km of classified forest roads in 1998 to 181,403 km in 2025, with nominal density over the GDF-constructed network rising from 7.30 to 9.90 m/ha between 1999 and 2025. The investment has been consistent and the results are visible. Construction accelerated markedly between 2019 and 2022, driven largely by a rapid expansion of tractor roads, whose cumulative length reached six times its 1998 baseline by 2025. Annual construction has declined sharply across all categories. These are real gains, and they should be recognized as such.

The global comparison complicates that picture. At 13.25 m/ha on the basis used for international comparison, Türkiye's current density sits within the Southeast European group but remains well below the values reported for countries such as Austria and Japan, where forest road planning has been function-driven for several decades. The twenty m/ha planning benchmark applies to the network planned and constructed by the GDF, which stood at 9.90 m/ha in 2025; at the average rate of increase recorded over the study period, it would not be reached within this century. The benchmark is not unrealistic in itself, since comparable densities have been achieved elsewhere, but closing the gap would require a different rate of progress.

The findings reported here are limited to national-scale nominal density derived from official construction statistics. Inferences about spatial distribution, road performance and environmental impact draw on the literature rather than on analysis carried out in this study and require verification at planning-unit scale.

Nominal density is a necessary metric but not a sufficient one: kilometers built say nothing about whether roads are located where they are most needed or evaluated for functional performance over time. The tractor road expansion makes this

concrete, and the harvesting system context sharpens it further. A tractor road network adds genuine value only where it is matched to tractor-based extraction. Türkiye's forestry institutions have the capacity for a more functional approach; GIS-based optimization tools, evaluation criteria that go beyond geometric standards, and a systematic monitoring protocol for tractor roads would be feasible additions to current practice.

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Data availability

The provincial forestry statistics analyzed during the current study were obtained from the General Directorate of Forestry (GDF) official statistics portal (GDF, 2025).

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Appendix

Table A1. Annual forest road construction by road category in Türkiye, 1998–2025 (km). Source: GDF (1998–2025)

Years	New Forest Roads (km)	Fire Safety Roads (km)	Tower Roads (km)	Tractor Roads (km)	Warehouse Road (km)
1998	1.524	538	20	154	62
1999	1.027	235	3	122	37
2000	1.115	206	3	178	40
2001	758	36	2	104	13
2002	950	73	7	206	15
2003	956	113	1	242	36
2004	1.000	152	7	289	53
2005	1.000	195	5	350	80
2006	1.000	162	2	439	143
2007	1.400	214	3	448	67
2008	1.600	336	9	500	85
2009	1.316	365	8	447	78
2010	1.400	469	4	431	120
2011	1.468	401	8	422	72
2012	1.518	379	21	448	92
2013	1.479	378	6	404	113
2014	1.542	310	10	443	100
2015	1.624	382	11	511	114
2016	1.852	324	4	751	171
2017	2.542	125	2	684	139
2018	2.902	169	3	969	147
2019	1.324	113	0	1.025	136
2020	2.675	173	0	1.538	167
2021	3.822	152	0	2.538	272
2022	6.865	374	2	2.740	199
2023	4.117	164	0	1.646	240
2024	2.158	255	6	1.098	225
2025	2.510	168	0	629	208
Average	1.909	249	5	706	115

Table A2. Cumulative total length of forest roads by category in Türkiye, 1998–2025 (km). Source: GDF (1998–2025)

Years	Forest Roads (km)	Fire Safety Roads (km)	Tower Roads (km)	Tractors Roads (km)	Warehouse Road (km)	Total (km)
1998	129.483	14.918	778	3.896	994	150.069
1999	130.510	15.153	781	4.018	1.031	151.493
2000	131.625	15.359	784	4.196	1.071	153.035
2001	132.383	15.395	786	4.300	1.084	153.948
2002	133.333	15.468	793	4.506	1.099	155.199
2003	134.289	15.581	794	4.748	1.135	156.547
2004	135.289	15.733	801	5.037	1.188	158.048
2005	136.289	15.928	806	5.387	1.268	159.678
2006	137.289	16.090	808	5.826	1.411	161.424
2007	138.689	16.304	811	6.274	1.478	163.556
2008	140.289	16.640	820	6.774	1.563	166.086
2009	141.605	17.005	828	7.221	1.641	168.300
2010	143.005	17.474	832	7.652	1.761	170.724
2011	144.473	17.875	840	8.074	1.833	173.095
2012	145.991	18.254	861	8.522	1.925	175.553
2013	147.470	18.632	867	8.926	2.038	177.933
2014	149.012	18.942	877	9.369	2.138	180.338
2015	150.636	19.324	888	9.880	2.252	182.980
2016	152.488	19.648	892	10.631	2.423	186.082
2017	155.030	19.773	894	11.315	2.562	189.574
2018	157.932	19.942	897	12.284	2.709	193.764
2019	159.256	20.055	897	13.309	2.845	196.362
2020	161.931	20.228	897	14.847	3.012	200.915
2021	165.753	20.380	897	17.385	3.284	207.699
2022	172.618	20.754	899	20.125	3.483	217.879
2023	176.735	20.918	899	21.771	3.723	224.046
2024	178.893	21.173	905	22.869	3.948	227.788
2025	181.403	21.341	905	23.498	4.156	231.303