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İÇİNDEKİLER

BETONARME KİRİŞLERİN EĞİLMEYE KARŞI GÜÇLENDİRİLMESİ

Kağan SÖĞÜT[1]

1. GİRİŞ

Betonarme yapılar; korozyon, zamana bağlı deformasyonlar, kullanım amacının değişmesi, malzemede meydana gelen bozulmalar ve işçilik kusurları gibi nedenlerle güçlendirmeye ihtiyaç duyabilir (Dirar vd., 2012; Dirar vd., 2013; ACI Committee 440, 2017). Modern standartlara uygun, daha rijit ve sünek betonarme elemanlar ancak uygun güçlendirme teknikleri kullanılarak yeniden kullanıma kazandırılabilir (Concrete Society, 2012; Chaallal vd., 2013; ACI Committee 440, 2017; Sogut vd., 2021). Bu nedenle, betonarme elemanların güçlendirilmesi konusu her geçen gün daha fazla önem kazanmakta; pek çok yenilikçi güçlendirme yöntemi araştırmacıların ilgi alanına girmektedir (Bui vd., 2020; Caro vd., 2023). Özellikle fiber takviyeli polimerler (FRP) ile yapılan güçlendirme teknikleri, FRP'nin üstün malzeme özellikleri nedeniyle sıkça tercih edilmiştir (Mofidi vd., 2012; Dirar vd., 2025). FRP kompozit malzemelerin temel avantajları arasında; hafif olmalarına karşın yüksek mukavemetli olmaları, korozyona karşı dayanıklılıkları ve kolay uygulanabilir olmaları sayılabilir (Teng vd., 2003; Wu ve Eamon, 2017; ACI Committee 440, 2017). Karbon, cam, aramid ve bazalt fiber takviyeli polimerler sıklıkla kullanılmaktadır (Oprisan vd., 2010). Ancak, Şekil 1'de

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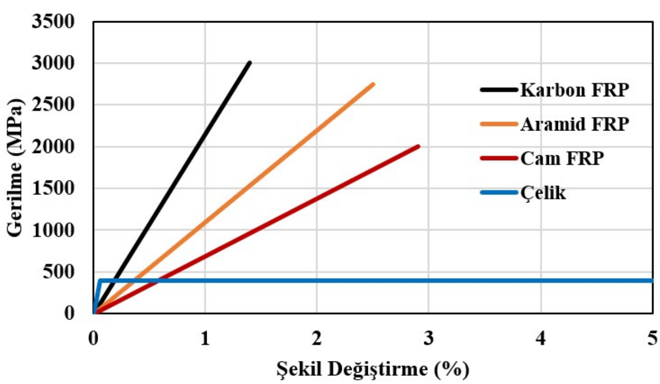
de gösterildiği üzere, FRP malzeme sünek değildir (Oprisan vd., 2010).

Betonarme kirişlerin eğilmeye karşı güçlendirilmesinde, dışarıdan yapıştırılan FRP kompozit kumaşlar (EB, ing. *externally bonded FRP*) ve yüzeye yakın monte edilen FRP çubuklar (NSM, ing. *near surface mounted FRP*) sıklıkla kullanılmaktadır (Nanni ve Norris, 1995; Kachlakev ve Mercurry, 2000; El-Hacha ve Rizkalla, 2004; De Lorenzis ve Teng, 2007; Ahmed vd., 2011; Reda vd., 2016; ACI Committee 440, 2017). Yüzeye yakın monte edilmiş FRP çubuklarla betonarme kirişlerin güçlendirilmesi yönteminde temel olarak aşağıdaki adımlar izlenir (De Lorenzis ve Nanni, 2001; De Lorenzis ve Teng, 2007).

- Beton yüzey üzerinde oluklar açılır. Olukların boyutu, kullanılacak FRP çubuğun çapına uygun ve aderansı sağlayacak şekilde olmalıdır.
- Açılan oluklar, epoksi ile yarıya kadar doldurulur.
- FRP çubuklar bu oluklara yerleştirilir ve hafifçe bastırılır. Böylece epoksi, çubuk ile oluk arasında boşluk kalmayacak şekilde aderans sağlar. Son olarak oluklar epoksi ile tamamen doldurulur ve yüzey düzeltilir (De Lorenzis ve Nanni, 2001; De Lorenzis ve Teng, 2007).

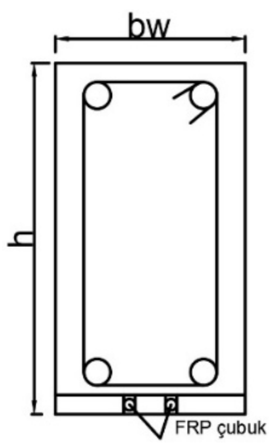
Şekil 1. Gerilme-şekil değiştirme ilişkileri (Oprisan vd., 2010)



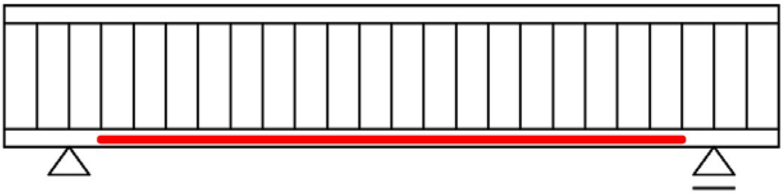
Yüzeye yakın monte edilmiş FRP çubuklarla eğilmeye karşı güçlendirilmiş tipik bir betonarme kiriş, Şekil 2'de verilmiştir. Betonarme kirişlerin, yüzeye yakın monte edilmiş FRP çubuklarla eğilmeye karşı güçlendirilmesine yönelik pek çok deneysel çalışma yapılmasına rağmen, güçlendirilmiş davranışını etkileyen parametreler henüz tam olarak anlaşılamamıştır (De Lorenzis ve Nanni, 2001; De Lorenzis ve Teng, 2007; Sharaky vd., 2015; Chennareddy ve Taha, 2017; Ali vd., 2022). Deneysel çalışmaların yürütülmesi, çoğu zaman zaman ve bütçe açısından zorlayıcı olabilmektedir. Betonarme kirişlerin eğilme altındaki davranışlarının, kesme davranışlarına kıyasla daha anlaşılır olduğu göz önüne alındığında, deneysel çalışmaları destekleyici nümerik modellemeler de yapılabilir. Bu çalışma kapsamında, Response-2000 (Bentz, 2000) programı kullanılarak yüzeye yakın monte edilmiş FRP çubuklarla eğilmeye karşı güçlendirilmiş betonarme kirişlerin davranışı incelenmiştir. Bu inceleme, özellikle moment-eğrilik ilişkileri üzerinden, farklı tip FRP çubuklar kullanılarak gerçekleştirilmiştir.

Şekil 2. Yüzeye yakın monte edilmiş FRP çubuklarla eğilmeye karşı güçlendirme (a) Enkesit (b) Boy kesit

(a)



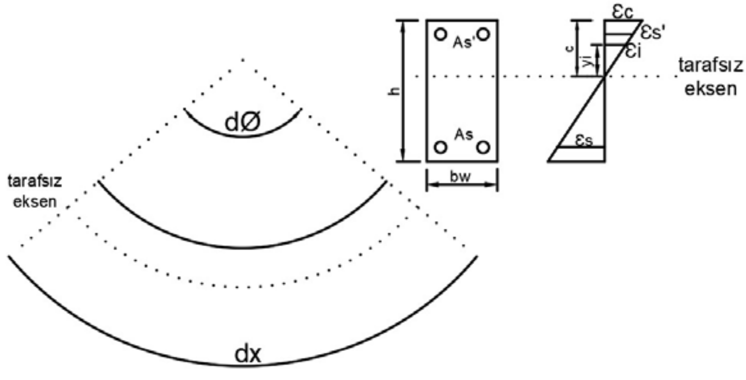
(b)



2. MOMENT-EĞRİLİK İLİŞKİSİ

Betonarme elemanların kesit davranışı moment-eğrilik ilişkileri üzerinden yorumlanabilir (Darılmaz, 2019; Ersoy vd., 2021). Örneğin, bir elemanın taşıma gücünde önemli bir düşüş olmadan deplasman veya deformasyon yapabilme yeteneği olarak tanımlanan süneklik, bu moment-eğrilik ilişkisi grafiği kullanılarak anlaşılabilir (Darılmaz, 2019; Ersoy vd., 2021). Yani, bir kesitin sünek olup olmadığı veya süneklik derecesinin ne olduğu, moment-eğrilik ilişkisine bakılarak yorumlanabilir Darılmaz, 2019). Eğrilik, birim dönme açısı olarak tanımlanabilir (Darılmaz, 2019). Şekil 3'te eğilme ve eksenel kuvvet altında bir kesit verilmiştir (Darılmaz, 2019; Ersoy vd., 2021).

Şekil 3. Eğrilik (Darılmaz, 2019; Ersoy vd., 2021)



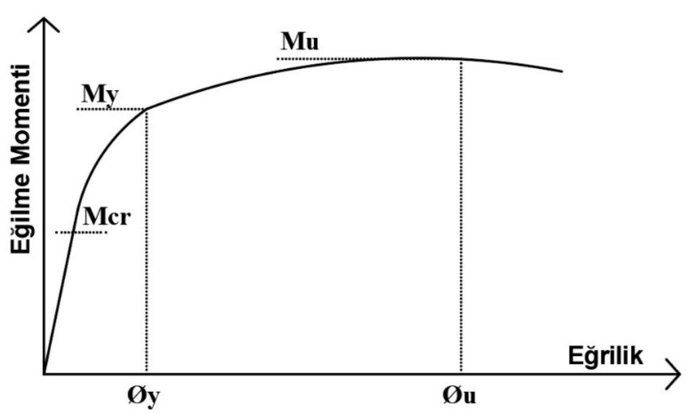
Eğrilik (K) Denklem 1'de gösterildiği gibi dönme açısı farkından veya kesitteki birim deformasyondan hesaplanabilir (Darılmaz, 2019; Ersoy vd., 2021).

$$Eğrilik = \frac{d\Phi}{dx} = \frac{d^2y}{dx^2} = \frac{1}{p} = K = \frac{\varepsilon_i}{y_i} = \frac{\varepsilon_c}{c} \quad (1)$$

Burada; c tarafsız eksen derinliği, ε_i tarafsız eksenden y_i mesafesinde oluşan birim şekil değiştirme, ε_c en dış basınç lifindeki birim kısalma ve p ise eğrilik yarıçapıdır.

Şekil 4'te, tipik eğilme etkisi altında betonarme bir kirişe ait moment-eğrilik grafiği verilmiştir (Darılmaz, 2019; Ersoy vd., 2021). Şekil 4'te gösterilen çatlama momentine kadar (M_{cr}) moment-eğrilik ilişkisi doğrusal olup, çatlak oluştuktan sonra doğrusal olmayan davranışa dönüşür. M_y ile ifade edilen moment değeri, kesitin donatısının akmasıyla birlikte oluşan eğilme momenti taşıma kapasitesini ifade eder. Bu momente karşılık gelen eğrilik ise $\boldsymbol{\Phi}_y$ ile gösterilmiştir. Grafikte betonarme kiriş maksimum eğilme momenti taşıma kapasitesine M_u ile ulaşmakta olup bu değere karşılık gelen eğrilik ise $\boldsymbol{\Phi}_u$ ile gösterilmiştir. Burada betonarme kiriş için süneklik, $\boldsymbol{\Phi}_u$ değerinin $\boldsymbol{\Phi}_y$ 'ye oranı ile hesaplanabilir (Darılmaz, 2019)

Şekil 4. Eğilme etkisi altında betonarme kirişin tipik moment-eğrilik ilişkisi (Darılmaz, 2019; Ersoy vd., 2021)



3. EĞİLMEYE KARŞI GÜÇLENDİRME

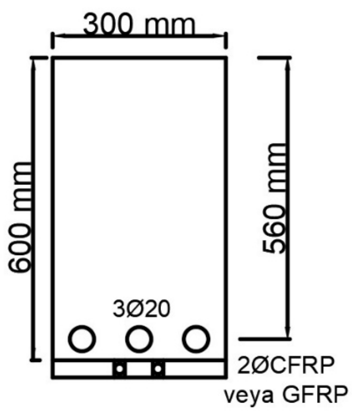
Yüzeye yakın monte edilmiş FRP çubuklarla betonarme kirişlerin eğilmeye karşı güçlendirilmesi durumunda, davranışın daha iyi anlaşılabilmesi için hem karbon hem de cam FRP (CFRP ve GFRP) çubuklar kullanılarak güçlendirme sistemi tasarlanmıştır. Her iki malzeme türü için 10 mm ve 13 mm donatı çapına sahip çubuklar kullanılmıştır. FRP çubuklara ait malzeme özellikleri Tablo 1'de gösterilmiştir (Aslan FRP).

Tablo 1. FRP Çubukların Malzeme Özellikleri

	Karbon FRP (CFRP) Çubuk	**Cam FRP (GFRP) Çubuk**
Çekme Dayanımı	2068 MPa	827 MPa
Elastisite Modülü	124000 MPa	46000 MPa
Kopma Şekil Değiştirmesi	0.017 mm/mm	0.018 mm/mm

Betonarme kirişler için enkesit detayları Şekil 5'te gösterilmiştir. Şekil 5'te de görüldüğü üzere, betonarme kiriş 600 mm yüksekliğe ve 300 mm genişliğe sahiptir. Pas payı 40 mm olup, kirişin etkili yüksekliği 560 mm'dir. Eğilme donatısı, üç adet 20 mm çapında çelik donatıdan oluşmaktadır.

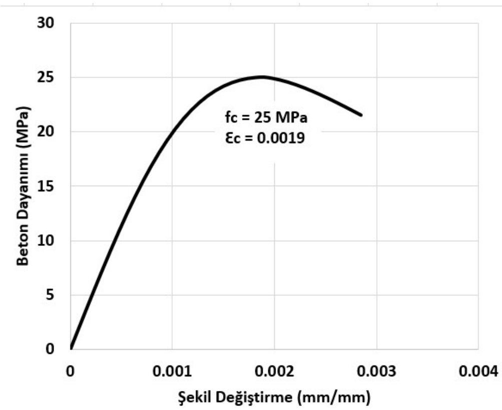
Şekil 5. Betonarme kiriş enkesit detayı



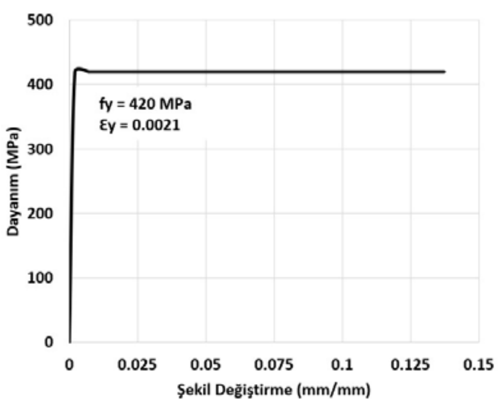
Çelik donatı akma dayanımı 420 MPa ve beton dayanımı 25 MPa olarak tasarlanmıştır. Betonarme kirişin eğilmeye karşı güçlendirilmesi için, yukarıda malzeme özellikleri verilen iki adet CFRP ve iki adet GFRP çubuğu kullanılmıştır. Analizler Response-2000 (Bentz, 2000) programı kullanılarak yapılmış olup, beton ve çelik malzemeler için kullanılan gerilme-şekil değiştirme ilişkileri Şekil 6'da verilmiştir. FRP çubuklar için ise Tablo 1'de gösterilen değerler kullanılarak oluşturulan doğrusal-gevrek (sünek olmayan) malzeme modeli uygulanmıştır.

Şekil 6. Malzeme modelleri (a) Beton, (b) Çelik

(a)



(b)



Response-2000 (Bentz, 2000) programı kullanılarak, yüzeye yakın monte edilmiş FRP çubuklarla güçlendirilmiş toplam dört adet betonarme kiriş analiz edilmiştir. Ayrıca, kontrol numunesi (güçlendirilmemiş betonarme kiriş) için de eğilme momenti kapasitesi hesaplanmıştır. Maksimum eğilme momenti taşıma kapasiteleri aşağıdaki Tablo 2'de verilmiştir. Tablo 2'den de anlaşılacağı üzere, yüzeye yakın monte edilmiş FRP çubuklarla yapılan güçlendirme yönteminde eğilme momenti kapasiteleri artmıştır. Örneğin, iki adet 10 mm çapında GFRP çubuk betonarme kirişin eğilme momenti kapasitesini yaklaşık olarak %32,9 (210.6 kN' dan 279.9 kN' a) artırmıştır. En yüksek kapasite artışı ise iki adet 13 mm çapında CFRP çubuk kullanılarak elde edilmiştir. Eğilme momenti kapasitesi 210.6 kN'dan 433.8 kN'a çıkmıştır. Bu da yaklaşık olarak %106 'lık bir artışa karşılık gelmektedir. Ayrıca FRP donatı çaplarındaki artışlar da eğilme momenti kapasitesinde artışlara sebep olmuştur. FRP donatı çapının 10 mm'den 13 mm'ye çıkarılması durumunda GFRP donatılarla güçlendirilmiş betonarme kirişin eğilme momenti kapasitesi yaklaşık olarak %15.8 artmış olup benzer şekilde CFRP donatılarla güçlendirmiş kirişte yaklaşık %16.5 'luk bir artış gözlenmiştir.

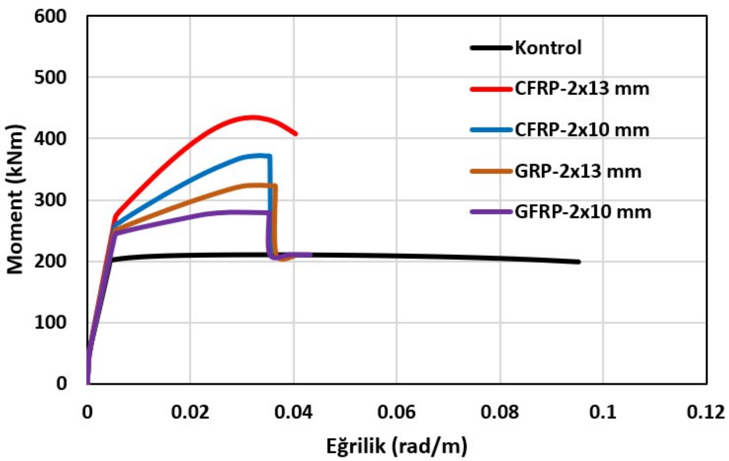
Tablo 2. Eğilme Momenti Kapasiteleri

Betonarme Kiriş	Eğilme Momenti Kapasitesi (kNm)
Kontrol	210.6
GFRP-2*10 mm	279.9
GFRP-2*13 mm	324
CFRP-2*10 mm	372.4
CFRP-2*13 mm	433.8

FRP çubuk malzeme tipinin eğilme momenti kapasitesi üzerine etkisi açıkça görülmüştür. Betonarme kirişi eğilmeye karşı güçlendirirken GFRP çubuklar yerine CFRP çubuklar kullanıldığı zaman eğilme momenti kapasitesinde yaklaşık %33' lük bir artış elde edilmiştir.

Şekil 7 güçlendirilmemiş (kontrol) ve güçlendirilmiş kirişlerin moment (kNm) – eğrilik (rad/m) ilişkilerini göstermektedir. Tüm kesitlerin çatlama momentine ulaşana kadar moment-eğrilik ilişkileri doğrusaldır. Kirişlerde çatlak oluştuktan sonra moment-eğrilik ilişkileri de doğrusal olmayan davranışa dönmüştür. Güçlendirilmemiş kirişin maksimum eğilme momenti karşılık gelen eğrilik değeri 0.033 rad/m olup, dönme sünekliği ise 7.4 olarak hesaplanmıştır. Şekil 7'den de görüldüğü üzere FRP çubuklarla birlikte moment kapasitesi artarken eğrilik değeri azalmıştır. Bu da FRP çubukların sünek bir malzeme olmamasıyla açıklanabilir. Dönme süneklikleri FRP çubuklar kullanılarak güçlendirmiş kirişlerde yaklaşık 5.56 olarak hesaplanmıştır.

Şekil 7. Moment-Eğrilik İlişkileri



5. SONUÇ

Yüzeye yakın monte edilmiş FRP çubuklarla eğilmeye karşı güçlendirilmiş betonarme kirişlerin davranışları incelenmiştir. Nümerik analizler Response-2000 (Bentz, 2000) programı kullanılarak yapılmıştır. Hem GFRP hem de CFRP çubuklar betonarme kirişin eğilme momenti kapasitesini artırmıştır. GFRP çubuklar, yaklaşık %32,9 ve %53,8 oranlarında eğilme momenti kapasitesini artırmıştır. CFRP çubukların kullanılması durumunda ise bu artış yaklaşık %76,8 ve %106 oranlarında gerçekleşmiştir. FRP donatı çapının artmasıyla eğilme momenti kapasitesi de artmıştır. FRP donatı çapının 10 mm'den 13 mm'ye çıkarılmasıyla birlikte, GFRP çubuklarla güçlendirilmiş betonarme kirişin eğilme momenti kapasitesi yaklaşık %15,8 artmış olup, CFRP donatılarla güçlendirilmiş kirişte ise benzer şekilde yaklaşık %16,5'lik bir artış gözlenmiştir. Kullanılan FRP malzeme tipinin de eğilme momenti kapasitesine etkisi incelenmiş olup, GFRP çubuklar yerine CFRP çubuklar kullanıldığında eğilme momenti kapasitesinde yaklaşık %33'lük bir artış elde edilmiştir. Moment-eğrilik ilişkileri hem güçlendirilmemiş hem de güçlendirilmiş kirişler için incelenmiştir. Dönme süneklikleri, FRP çubuklar kullanılarak güçlendirilmiş kirişlerde yaklaşık 5,56 olarak hesaplanmıştır.

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THE IMPORTANCE OF HYDRAULIC AND HYDROLOGIC ANALYSES IN DESIGNING TRANSPORTATION STRUCTURES

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1. INTRODUCTION

The term "transportation structures" refers to the infrastructural systems that are constructed to guarantee the secure, rapid, and effective movement of both people and goods from one location to another. These structures include a variety of modes of transportation, including rail, air, sea, and road transit, among others. Highways, bridges, tunnels, intersections, and viaducts are the types of fundamental structures that are necessary for the operation of road transportation. Different types of roads, such as highways, urban roads, and village roads, are distinguished from one another. These roads are responsible for regulating vehicle traffic and enhancing safety. Among the components of railways are the rail systems that guarantee the rapid and secure movement of trains. Railway infrastructure is comprised of a number of essential components, including stations, viaducts, tunnels, and signaling systems. Ports, piers, breakwaters, and shipyards are the key components that make up the maritime transportation system. Ships can be docked safely, and loading and unloading operations may be carried out more

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efficiently thanks to these buildings. Airports are intricate buildings that serve for the purpose of facilitating the landing and takeoff of airplanes as well as providing facilities to passengers. Runways, terminals, towers, and maintenance hangars are all essential components that contribute to the increased safety and efficiency of air transportation when they are assembled. The establishment of transportation infrastructure is an essential component in the growth of contemporary society. The development of an effective transportation infrastructure is beneficial to the expansion of the economy, the improvement of social life, and the control of urbanization. It is important to note that the design principles of transportation infrastructure differ depending on the type of construction being constructed (road, railway, airport, etc.). Nevertheless, the following is a list of the fundamental design concepts that must to be taken into consideration for every transportation structure in this context:

When designing highways, the following are the primary considerations to take into account:

Traffic Volume: At the time of capacity determination, both the current and future traffic load are taken into consideration.

The load-bearing capacity and drainage properties of the soil on which the road rests are taken into consideration during the design process for the foundation and the soil around the road.

Pavement Design: The load of traffic is taken into consideration while choosing the materials for the pavement, which may include asphalt or concrete.

The placement of barriers, road markings, lighting, and traffic signs are all part of the security measures that are chosen.

Drainage System: Drainage systems that are suitable for the rapid discharge of rainwater are constructed using appropriate methodologies.

Factors to take into account when designing a railway:

Line Geometry: The slope of the line, the radius of the curve, and the maximum speed are all determined by taking into consideration these criteria.

The selection of rails and sleepers involves determining the type of rails and sleepers that will be utilized, as well as their durability.

Ballast and Ground Stability: It is assured that the ground on which the railway line hangs has suitable load-bearing capability. This is done to ensure that the line is stable.

Design of Bridges and Tunnels: The structures of the bridges and tunnels that are required by the terrain are estimated and planned.

Signaling and Electrification: In order to ensure the safety of train traffic, signaling systems are being planned.

The following are important aspects to consider when designing an airport:

Runway Design: This involves determining the required length, width, and surface characteristics for aircraft takeoff and landing.

Taxiways and Apron: These are organized to ensure that airplanes are able to move around safely.

The design of the terminal building and passenger flow is based on the number of passengers that will be present. For the Air Traffic Control System, radar and tower control systems are incorporated into the system. These concepts are the fundamental engineering principles that have been established to guarantee that every transportation construction is safe, efficient, and long-lasting. Depending on the country and the rules, the specifics could be different (Bedient et al. 2011, AASHTO 2017).

2. THE IMPORTANCE OF DEVELOPING TRANSPORTATION STRUCTURES IN ENGINEERING

In terms of economics, safety, the environment, and society, the design of transportation structures (such as highways, railways, airports, and ports, among other things) is of utmost significance. One can investigate the significance of design by looking at it through the following categories:

2.1. Safety

Roads, railroads, and airports that are well-designed assist reduce the likelihood of accidents occurring. By controlling the flow of traffic, it lessens the likelihood of collisions occurring. The safety of motorists and pedestrians is improved when features like as roadside barriers, lighting, signaling, and drainage are designed in the appropriate manner.

2.2. Comfort and Efficiency

Through the maintenance of a continuous and unbroken flow of traffic, the level of comfort experienced while driving is improved. It is possible for drivers to experience less fatigue when the slope, bends, and breadth of the road are constructed appropriately. Waiting times can be cut down significantly by improving the efficiency of the logistics procedures at airports and ports.

2.3. Contribution to the Economy and Cost-Effectiveness Assessment

Costs associated with maintenance and repairs are reduced when designs are long-lasting and durable. Transportation networks that have been carefully laid out are a significant factor in the growth of both industry and commerce. Enhancing economic efficiency can be accomplished by analyzing several alternative routes and modes of transportation.

2.4. Environmental Impacts

By reducing the amount of time spent in traffic, it lowers the amount of gasoline used and the amount of carbon emissions produced. The conservation of water resources is facilitated by drainage systems that have been designed in an appropriate manner. The implementation of solutions that contribute to the reduction of noise and air pollution, such as noise barriers, is possible.

2.5. The Relationship Between Urban Planning and Social Impacts

The organization of the growth of cities is supported by the proper planning of transportation infrastructure. Because it makes transportation more accessible, the integration of public transportation systems helps to minimize socioeconomic inequality. By reducing the amount of time spent in traffic, it enhances the overall quality of life. Structures that are designed to be resilient and resistant to natural catastrophes, such as earthquakes and floods, contribute to a reduction in the risks that are associated with them. It is possible to speed up the process of performing emergency interventions by developing alternative transportation routes (Chow et al. 1988, Chanson 2004, Federal Highway Administration 2017).

3. FUNDAMENTALS OF HYDRAULIC AND HYDROLOGIC ANALYSES

Transportation structures are vital components of the infrastructure that guarantee the secure and effective movement of people, products, and services. Nevertheless, because these structures have direct interactions with the natural environment, it is essential to take into consideration environmental and natural elements during the design phase. Among them, the hydraulic and hydrological assessments that are associated with water resources and water flows are among the most essential variables. Hydraulic and hydrological assessments are studies that are carried out in order to gain an understanding of the flow of water in the region where a transportation project will be created and to produce engineering solutions that are suitable for the situation. The identification of flood risks, the evaluation of the impact of water on infrastructure, the design of drainage systems, and the guarantee of environmental sustainability are all outcomes that are significantly influenced by these assessments. Incorrect or insufficient hydraulic-hydrological studies can result in early damages, erosion problems, floods, and environmental degradation in transportation structures. These issues can be caused by construction defects. As a result, one of the key prerequisites for the development of a transportation infrastructure that is both secure and long-lasting is the incorporation of hydrological and hydraulic assessments into engineering procedures (Hydrologic Engineering Center 2016, Garber and Hoel 2019, USGS 2020).

Structures for transportation, such as highways, tunnels, bridges, and culverts, are not constructed in a vacuum, but rather in close proximity to the natural environment. A comprehensive comprehension of the ways in which water interacts with these structures is essential to the long-term functionality and safety of these buildings. The results of hydraulic and hydrologic evaluations provide crucial insights that are used to guide design decisions. These insights help to ensure that transportation infrastructure is robust, sustainable, and safe in a variety of environmental situations (Khisty and Lall 2017, Papacostas and Prevedouros 2015). The primary functions that these studies serve, the approaches that are utilized, and the influence that they have on contemporary transportation engineering are all discussed in this chapter. Infrastructure responsible for transportation must be able to withstand a wide variety of environmental difficulties. It is important to note that water-induced forces are among the most significant of these. If the integrity of structures is not adequately anticipated during the design process, then flood events, sediment transport, erosion, and scouring can all jeopardize the integrity of the structures (French 1986, Linsley et al. 1992, Sturm 2010). Hydraulic and hydrologic assessments are systematic examinations that assist engineers in understanding the behavior of water, including its amount, flow patterns, and the forces that it exerts, and in predicting how these factors can affect transportation infrastructure throughout the course of their lifetime. The purpose of this chapter is to delve into the theoretical foundations, practical applications, and issues that are connected with the incorporation of hydrologic and hydraulic assessments into the design of transportation infrastructure.

3.1. Using Hydrologic Analysis to Determine the Movement of Water and Its Quantity

Studying the water cycle and determining the quantity of water as well as its distribution within a watershed are both components of the process known as hydrologic analysis. Among the most important aspects are:

The process of determining the amount of precipitation or snowfall that contributes to runoff, which ultimately results in streamflow, is referred to as precipitation and runoff. When it comes to estimating peak flow rates during storm events, this is quite important.

The evaluation of the rate at which water infiltrates the earth and the role that natural or manmade storage (such as wetlands and retention basins) plays in modifying flood peaks is referred to as "infiltration and storage."

Assessment of the ways in which seasonal shifts and climate variability influence the availability and distribution of water is referred to as temporal variability. When it comes to anticipating the severity of floods, constructing drainage systems, and defining safety margins in engineering projects, having accurate hydrologic data is absolutely necessary.

3.2. Examination of Hydraulics

Familiarizing oneself with water flow and forces during hydraulic analysis, the behavior of water as it flows through and around structures is the primary focus of attention. What it includes is:

Regimes of flow and understanding the difference between laminar and turbulent flows, as well as subcritical and supercritical states, is something that is absolutely necessary in order to comprehend the process of energy dissipation. The evaluation of how the form and roughness of channels influence flow velocity, pressure distribution, and possible areas of erosion is referred to as channel geometry and flow characteristics. The process of predicting the removal of silt around foundations and abutments, which can cause a structure to become weaker or possibly collapse over time, is referred to as scour and erosion.

Engineers are able to simulate the behavior of water under a variety of settings, discover vulnerabilities, and build structures that successfully manage and resist water forces through the use of hydraulic analysis.

3.2.1. Integration with the Design of Bridges and Culverts

Certain structures, such as bridges and culverts, are especially susceptible to the effects of water.

Using the analysis, engineers are able to determine: Engineers ensure that bridges have adequate clearance to minimize water-induced damage by estimating the water levels during extreme events. This is accomplished by anticipating the water levels that will be present during the event. Hydraulic models are used to forecast the erosion that occurs around bridge piers and abutments because of the scour protection. This information is utilized in the process of designing scour protection measures, which may include riprap, concrete aprons, or deep foundations.

The pressures that are exerted by moving water can be enormous, thus it is important to take load and impact into consideration. Engineers are able to design structures that are capable of withstanding dynamic loads without compromising their stability with the help of their understanding of these forces.

3.2.2. The Drainage of Roadways and Highways

In order to keep roadways safe and to extend the life of the pavement, it is essential to have drainage systems that are effective. The contributions of hydrologic and hydraulic analysis include the following: -In the design of drainage networks: Calculating the amount of runoff that is anticipated from different levels of rainfall is helpful in determining the appropriate size of culverts, ditches, and storm sewers used to minimize water accumulation.

Reducing the Risk of Hydroplaning and Surface Damage

Proper drainage helps to reduce the amount of water that pools on road surfaces, which in turn reduces the likelihood of hydroplaning and the formation of potholes.

Enhancing Pavement Durability

These analyses contribute to the longevity of the road construction by controlling the passage of water and preventing the subgrade from becoming saturated.

Protection Barriers and Tunnels for Flooding Hazards

However, the stakes are significantly higher when it comes to tunnels and flood barriers. Hydrologic assessments are used to ensure that tunnels are protected against water infiltration during high-water occurrences. Hydraulic analyses, on the other hand, are used to advise the design of barriers that can redirect or confine water flows without failing.

Long-term precipitation records are a useful tool for modeling future runoff occurrences, according to meteorological data. Detailed elevation data are necessary for proper mapping of watersheds and channels, which can be obtained by topographical surveys.

For the purpose of calibrating models, stream gauges and historical flood records are crucial sources of flow data dating back in time.

4. HYDRAULIC AND HYDROLOGICAL ANALYSES

The following are the two primary disciplines that are typically included in hydraulic and hydrological analyses:

The principles of fluid mechanics are utilized in hydraulic analyses, which involve the investigation of the movement of water. During hydraulic assessments, the speed, pressure, flow type, and carrying capacity of water are the primary factors that are determined.

Those who are concerned with the water cycle and the administration of water resources in a region are the ones that do hydrological analyses. Precipitation, evaporation, surface runoff, groundwater movements, and flood projections are some of the subjects that are covered in this chapter.

Both of these assessments are taken into consideration jointly, and the ways in which transportation projects interact with water are examined in great depth.

5. THE IDENTIFICATION AND AVOIDANCE OF THE DANGER OF FLOODING

Highways, bridges, and tunnels are examples of transportation constructions that frequently have to traverse riverbeds, valley bottoms, and low-lying terrain in order to reach their destinations. These kinds of regions are at a significant danger of flooding as a result of unexpected rainfall. When it comes to predicting the amounts of water rise, hydrological calculations are helpful since they determine the flood flows in the region. As a result, it is made certain that the structures that are used for transportation are constructed at the suitable elevation, and that the drainage measures that are required are implemented. As an illustration, the determination of the openings of bridges or culverts is accomplished by calculating the 100-year flood discharge, also known as Q100. Because of the failure to do these evaluations, culverts that have insufficient apertures or roadways that are not leveled properly have the potential to be inundated, which can result in major economic losses and safety hazards. In the design of bridges and viaducts, hydraulic and hydrological analyses are performed.

When it comes to transportation, bridges are essential constructions that are constructed over rivers or streams. The direction of water flow, the distribution of velocity, and the amount of silt that the water carries are all factors that need to be carefully considered while designing a bridge. Through the utilization of hydraulic analyses, it is possible to ascertain whether or not the bridge piers are resistant to the erosive impacts that water can have. Scour, which is the erosion of the ground around bridge piers as a result of the action of water, is one of the particular factors that might cause the structure to lose its stability. For the purpose of identifying such dangers, hydraulic modeling software such as HEC-RAS and MIKE 21, among others, is utilized to simulate the flow of water, and the appropriate measures are implemented during the design process of bridges.

5.1. Conceptualization of Drainage Devices

Drainage systems are installed in transportation infrastructure to provide the safe disposal of surface waters, which prevents water from accumulating on the surface of the road. It is possible to build rainwater drainage systems, channels, and culverts with the help of hydrological assessments, which also allow for the determination of the rainfall pattern in the region as well as the locations where water accumulates.

In the event that suitable drainage arrangements are not made:

Water builds up on the surface of the road, which raises the possibility of hydroplaning, which is the act of sliding on a cushion of water, and ultimately leads to accidents in the roadways.

It is possible for the ground beneath the road to get saturated with water, which can result in ground settlements and present the possibility of subsidence.

The structural integrity of roadways can be jeopardized when surface waters are directed in an incorrect direction, which can lead to erosion and landslides.

5.2. Evaluation of Hydrological Conditions with Regard to the Stability of Tunnels and Slopes

The relevance of hydrogeological investigations cannot be overstated when it comes to tunnels because they are typically excavated in mountainous terrains or on grounds that are soaked with water. In order to guarantee that the tunnel is water-resistant, it is necessary to conduct a comprehensive investigation of the groundwater level, water pressure, and the characteristics of impermeable layers.

Except in the event that groundwater seeps into the tunnel, the following will occur: The gradual failure of concrete structures due to wear and tear over time Decrease in the safety of transportation as a result of the accumulation of water. It is possible that there will be problems, such as an increase in the price of operation and maintenance.

The planning and design of transportation infrastructure typically make use of these methodologies, which are the engineering tools that are employed the most frequently.

5.3. Performing Hydrological Analyses

The field of hydrology is concerned with the investigation of hydrometeorological phenomena, which include the study of precipitation, flow, water buildup, and flooding. During the design process, transportation infrastructure must to take into consideration the flow and impact of water. In the event that this does not occur, significant issues such as erosion, the risk of flooding, the disappearance of bearing capacity in the ground, and structural damage may occur.

Analyses of floods are performed in order to ascertain whether or not roads and bridges are susceptible to flooding. During a flood, roads may be closed or bridges may sustain damage if the drainage systems are not adequate enough to handle the water.

Design of Drainage Systems: In order to remove water from the surface of the road, it is required to have drainage systems that are appropriate. One of the consequences of inadequate drainage is the collection of water, which can cause the road surface to deteriorate.
Stability of the Soil: A high water content can diminish the carrying capacity of the soil, which can lead to settlement and surface sliding on roads and railways.
Control of Erosion: This process involves determining the steps that need to be taken in order to prevent erosion from occurring along the roadside as a result of precipitation and surface runoff.

Dam and Pond Effects: Dams and ponds that are situated in close proximity to transportation structures have the potential to influence the level of groundwater, which in turn can modify the stability of the structures.

6. ADVANTAGES OF CONDUCTİNG HYDROLOGİCAL ANALYSES

6.1. Long-lasting and secure structures

When hydrological data is taken into consideration, roads and bridges become safer over the course of their lifetimes.

Reduction in the Costs of Maintenance and Repairs When water-related damages are reduced to a minimum, maintenance costs are also reduced.

Transportation projects that are environmentally conscious are constructed by protecting the natural water flow. This is done in order to ensure environmental sustainability. A reduction in the risk of disaster occurs when structures become more resistant to the effects of natural disasters such as flooding and waterlogging.

In conclusion, it is of utmost significance that hydrological analyses be carried out in a manner that is both precise and comprehensive when it comes to the construction of transportation structures. Based on the findings of these evaluations, it is possible to carry out projects that not only adhere to engineering standards but also reduce their negative effects on the environment. When it comes to the design of transportation structures, hydrological assessments are of the utmost importance for ensuring the structures' operation, longevity, and safety. The purpose of these assessments is to investigate hydrological processes such as the flow, distribution, and quality of water. This will ensure that transportation infrastructure is able to adjust to the conditions of the environment and is protected from those that could have negative impacts.

Identifying and Managing the risks associated with flooding. Hydrological evaluations are extremely important, particularly when it comes to predicting the likelihood of flooding. Floods have the potential to inflict significant damage to transportation structures as well as disruptions to service. As a result, the construction of buildings like bridges, roads, and tunnels requires an accurate prediction of the likelihood of flooding as well as the potential water levels. There is the potential to create structures that are resistant to the risk of flooding and have a long lifespan provided correct hydrological data is readily available.

6.2. Measures to Prevent Erosion and Sedimentation

The movement of water can cause erosion and sedimentation issues in regions where transportation structures are situated. These issues can be caused by transportation structures. The ability to understand and exert control over these processes is made possible by hydrological analysis. For instance, erosion that may take place along the edges of roads or bridge piers might pose a threat to the structure's ability to remain stable. The safety of structures can be improved by the early identification of potential dangers and the application of engineering solutions that are suitable for the situation (Budhu 2010, Das 2013).

6.3. The Management of Water Resources in a Sustainable Manner

Another factor that contributes to the efficient and long-term management of water resources is the utilization of hydrological assessments. When designing transportation structures that are directly tied to water, such as dams, canals, and drainage systems, it is especially important to take into consideration the existing state of water resources as well as to anticipate any changes that may occur in the future. The efficient use of water can be ensured in this manner, thereby reducing the negative effects on the environment. Significant alterations are being brought about in the patterns of precipitation and water supplies as a result of climate change. Hydrological evaluations make it possible to make predictions about the potential implications that these changes could have on transportation structures. This makes it possible to take the appropriate measures during the design phase of the planning process. For instance, elevated levels of precipitation and the occurrence of severe weather can both contribute to an increased likelihood of flooding. Consequently, it is of the utmost importance to plan transportation infrastructure in such a way that it is both resilient and adaptable to climate change. The necessity of hydrological assessments in the design of transportation structures is absolutely necessary in order to ensure the structures' safety, longevity, and compatibility with the surrounding environment while they are being constructed. Hydrological evaluations that are both accurate and comprehensive ensure that transportation infrastructure is prepared to withstand the effects of natural disasters and can continue to function in a sustainable manner over the long term.

7. HYDROLOGICAL PARAMETERS THAT ARE MOST IMPORTANT

*The amount of precipitation and the intensity for it:*When it comes to estimating surface runoff and determining the appropriate size of drainage systems, the average and maximum rainfall values in the region are extremely important pieces of information.

Runoff from the land: The degree to which the road is exposed to water is determined by the amount of water that runs on the surface after it has accumulated after it has rained. This is predicated on a number of elements, including the slope of the road surface, the kind of soil, and the land use.

Characteristics of the Soil: Both the soil's ability to absorb water and the amount of water that runs off the surface are influenced by the kind of soil, its permeability, and its drainage capacity. The accumulation of water on the surface can be caused by soils that have a low permeability, such as clay.

The Level of Groundwater: When groundwater levels are high, it can cause the foundation of the road to get saturated, which can result in structural issues. As a result, it is essential to ascertain and maintain control over the groundwater level.

Danger of Flooding: In the event that the road route is located in close proximity to rivers, streams, or other bodies of water, the likelihood of flooding significantly increases. With the help of flood analyses, one can gain direction regarding the positioning and height of the road.

The topography and the slope: The direction and speed of water flow are both affected by the slope of the land as well as the general topography of the land. On the other hand, flat terrains may experience water accumulation, while steep slopes can allow water to flow swiftly, which can sometimes lead to erosion.

Rise in Capillaries: Due to the phenomenon of capillarity, it is possible for groundwater to rise to the surface of the road, particularly in soils with fine grains. This circumstance has the potential to cause harm to the surface of the road.

The hydrological soil groups and the curve number, also known as the CN: The CN value, which is arrived at by taking into account the type of soil and the land usage, is utilized in the process of forecasting surface runoff. Elevated CN readings are indicative of increased surface runoff.

After the planning and design stages of road construction have been completed, it is of the utmost importance to conduct an accurate evaluation of these characteristics. When it comes to the construction of adequate drainage systems, erosion control, and the long-term performance of the road, hydrological analyses serve as the foundation.

The following is a list of hydrological criteria that should be taken into consideration when building roads and other resources associated to them:

Characteristics of the Basin: There are a number of critical characteristics that influence the flow regime and the risk of flooding. Some of these factors include the size of the river basin, the terrain, the structure of the soil, and the vegetation cover.

Transportation of Sediment: The amount of silt that is carried by the stream, as well as its potential for buildup or erosion, should be examined in relation to the span of the bridge and the location of its piers. This collection of sites offers information that is both extensive and technical regarding the hydrological characteristics that are significant in the construction of bridges.

In the context of transportation constructions, hydraulic studies are exams that are carried out to ensure the safety of infrastructure by evaluating the hazards of flooding and excessive water flow. These assessments are especially significant for constructions like bridges, culverts, highways, railways, and drainage systems. It is also important for drainage systems.

The following is a list of the primary type of hydraulic analysis:

7.1. Investigations of Stream Hydrology

Calculations of Flow: The amount of water that rivers carry is determined by these calculations. When doing flood analyses, the possible flood discharges of structures are calculated in order to assess their level of safety.

In hydraulic profiles, the levels of water are determined by calculating the water levels along the river's cross-sections.

Analyses of Hydraulic Behavior in Culverts and Bridges: Both free and pressurized flow controls are analyzed to determine whether or not the vents and bridge apertures are adequate. As part of the analysis of erosion and scour, the danger of scour is evaluated at the bridge piers and inlet-outlet zones of culverts. For the purpose of ensuring that bridges and culverts continue to be below the acceptable water level, calculations are performed to determine the maximum flow height.

7.2. Assessments of the Drainage System

Precipitation Runoff Modeling: The amount of precipitation is used to determine the amount of runoff that is generated from the surface. An examination of the capacity of drainage channels is performed in order to determine whether or not water is effectively drained for roads and railways.

The manner in which impermeable surfaces, such as asphalt and concrete, influence the flow of water is analyzed.

Analysis of the Hydrodynamics of Coastal and Port Areas: The ability of marine structures to withstand the effects of waves and currents is investigated through the use of wave and current analyses.
Coastal constructions are evaluated for the possibility of being filled or degraded over time as part of the sediment transport process

Evaluations of Groundwater and Leakage Studies: An investigation is carried out in order to determine the level of groundwater in order to prevent water pressure from causing harm to the infrastructure of roads.
This study investigates the impact that water has on tunnels and deep excavations through the use of seepage and drainage controls.

The rise in groundwater levels can have a detrimental impact on the infrastructure of transportation and lead to significant engineering issues.

7.3. Main Effect

7.3.1. Reduced Capacity to Maintain Soil Stability

A rising groundwater level causes the soil to become more saturated, which in turn reduces the soil's capacity to support loads.

It is possible for it to cause the materials that make up road and railway embankments to become loose and settle. In particular, clay-containing soils are more likely to experience deformations as a result of the impacts of swelling and shrinking.

7.3.2. Changes in the Road System and Settlements

It is possible for the loosening of infrastructure materials to occur as a result of an increase in water pressure, which can then lead to road subsidence.

The risk of soil liquefaction is increased, particularly when additional loads are applied, such as during an earthquake, which causes the soil to lose its capacity to sustain loads. On railway lines, there is a possibility of seeing rail distortions and settlements.

7.3.3. Failure of Drainage Systems to Meet Needs

It is possible for surface water drainage systems to become less effective when groundwater levels are high.

Through the process of backflowing in drainage channels and vents, it can lead to the accumulation of water.

The likelihood of flooding is increased in tunnels and metro lines that are part of the infrastructure.

7.3.4. Pavements made of asphalt and concrete are deteriorating

The cracking of asphalt and concrete surfaces is caused by the saturation of the material beneath the surface, which is caused by the cycles of freezing and thawing.

Minerals and soluble salts have the potential to rise to the surface together with groundwater, which can result in the degradation of materials (also known as efflorescence).

7.3.5. There is a potential for erosion and settlement at the bridge and culvert abutments.

Elevated groundwater levels have the potential to deteriorate the soil around the bridge piers, hence amplifying the scouring impact.

The longevity of the infrastructure is diminished when fine-grained debris is transported by water flow, which is more commonly known as erosion.

7.3.6. It is possible for tunnels and underground passageways to become flooded.

It has the potential to create uncontrolled water infiltration into subsurface infrastructure, which ultimately disrupts operations.

Long-term damage can be caused by issues with waterproofing in reinforced concrete structures as well as corrosion of the reinforcing.

In order to avoid aforementioned problems, it is necessary to establish groundwater management solutions, such as pump systems and drainage wells, as well as drainage systems, ground improvement methods, waterproof coatings, and groundwater improvement methods. The meticulous study of the groundwater level and the execution of appropriate technical solutions are of crucial importance, particularly in the context of massive infrastructure projects.

8. CONCLUSION

It is imperative that transportation infrastructure be designed in such a way that they allow for the safe, rapid, and effective movement of both people and products. In addition to fostering economic growth, this also contributes to the preservation of the environment and the improvement of social welfare. Due to the fact that even little errors that occur during the design phase can result in major expenses or even loss of life, it is of the utmost importance to prepare in line with engineering principles and standards.

It is of the utmost importance to carry out complete hydraulic and hydrological evaluations prior to the building of transportation structures. This is necessary in order to ensure that these constructions are both safe and durable. In order to reduce the impact that water has on the structure, it is important to take into consideration a variety of factors, including the potential for flooding, drainage systems, the design of bridges and viaducts, and the safety of tunnels. In the case that these studies are either insufficient or inaccurate, there is the potential for major economic losses, damage to the environment, and hazards to the physical safety of individuals. Therefore, in order to make transportation infrastructure safer, more sustainable, and more resilient, engineers and urban planners should utilize contemporary approaches for hydraulic-hydrological analysis.

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TYPES OF COATINGS IN GROUND-LEVEL CROSSINGS AND THE ADVANTAGES OF USING RUBBER COATING IN CROSSINGS

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1. INTRODUCTION

Transportation is a service that enables the movement of people or goods to meet their needs by providing benefits of time and space. Railway; it is called a train, which consists of a series of vehicles that pull and are pulled, moving on a pair of rail tracks and the facilities that make up this series (Kozak 2010). The railway consists of two main sections: infrastructure and superstructure. Static and dynamic forces from railway cars come from the wheels to the superstructure and then pass to the substructure. In railways, the part of the structure that sits on the substructure platform is called the superstructure. The elements that make up the superstructure are rails, sleepers, ballast, and small track materials (Bozkurt 1989).

As in all transportation systems, the main goal in rail systems is safe transportation (Rumsey 2006). Although the studies conducted on this issue within today's rapidly developing technology aim to reduce traffic errors, mistakes on railways still often result in fatal major accidents (Kuepper 1999). In order to prevent accidents, it is necessary to ensure the safety of the level

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crossing areas (grade crossings) where railway accidents are most frequent and to carry out the necessary work.

The planning, design, and reorganization of existing level crossings to meet appropriate standards, among other practices, have gained importance in our country's railways in recent years, just as they have worldwide.

In developed countries around the world, although many regulatory efforts are made to ensure traffic safety at level crossings, minimize accidents that may occur in these crossing areas, and increase comfort to speed up traffic flow, various issues are still encountered at these intersection areas. At the root of these problems are factors such as the inadequate analysis of level crossing elements, the inability to operate level crossings at an appropriate service level, and the prioritization of financial policies over safety measures, among others.

2. RAILROAD CROSSINGS

The term "passage" is defined as a place that enables passage or makes crossing normal. As a definition of transportation, they are facilities that allow vehicles and pedestrians to pass from one section of the railway to another without risking their safety and property in areas where the railway intersects with the road or pedestrians. The selection and design of railway crossings depend on many parameters, but based on the physical condition and geometry of the railway, there are three types of crossings: overpass, underpass, and at-grade crossing (Bozlioğlu 2017).

2.1. Safety

According to the Highway Traffic Regulation, an overpass, defined as a structure that allows a road to pass over another road or railway, can also be described as an artistic structure built to ensure that traffic users in the relevant areas can pass over it without obstructing the existing road or railway traffic. Since railway vehicles such as trains will pass under the bridge to be used as an overpass, the clearance, known as the gabari, under the overpass should not be smaller than the gabari of the railway structure. One of the purposes of constructing overpasses is not to disrupt the flow of traffic.

Figure 2.1. Example of an overpass (Sakarya-Arifiye railway overpass) (Bozlioğlu 2017)

2.2. Underpasses

An underpass is a term used for artistic structures, mostly built as box sections, that are constructed under an existing railway line to separate a roadway from a railway, a pedestrian path from a railway, or one railway line from another. In train stations, there are underpasses built to allow passengers to change platforms, as well as instances where the new Ankara-Eskişehir high-speed train line overlaps with the old train line, resulting in the mentioned railway lines being either overpasses or underpasses in relation to each other.

Figure 2.2. Underpass example (Istanbul-Bostancı railway underpass) (Bozlioğlu 2017)

2.3. At-grade (Level) Crossings

The crossings where the road and railway intersect at the same level, with or without barriers, are called level crossings, also known as railway crossings. Many factors should be taken into account in the design of level crossings.

Figure 2.3. Example of a level crossing (Aydın-Söke railway) (Bozlioğlu 2017)

3. AT-GRADE (LEVEL) CROSSING AND ITS TYPES

Level crossings (at-grade crossings) refer to places where a road and a railway intersect at the same level. In terms of the safety of level crossings, they can be examined in three types: unguarded without barriers, guarded with barriers, and guarded with automatic barriers. The statistics of the number and types of level crossings by year are provided in Table 3.1, and it is observed from the chart that the number of crossings has significantly decreased over the years, while the number of protected crossings has increased.

Table 3.1. The number of level crossings by year (TCDD 2021).

Years	Level crossing number of crossings	Controlled level crossing number of crossings
2000	4.630	410
2001	4.577	407
2002	4.810	405
2003	4.520	558
2004	4.280	597
2005	4.078	655
2006	4.015	751
2007	3.850	948
2008	3.854	846
2009	3.555	1.027
2010	3.476	1.029
2011	3.418	1.056
2012	3.351	1.055
2013	3.314	1.062
2014	3.110	1.068
2015	3.110	1.068
2016	3.010	1.074
2017	3.010	1.079
2018	2.909	1.045
2019	2.788	1.127
2020	2.681	1.188

3.1. At-Grade (Level) Crossings

During the approach of railway vehicles to level crossing areas, protective structures that provide some level of traffic safety by blocking the area for road users (road vehicles, pedestrians, etc.) are called barriers. Level crossings without barriers and attendants are the most commonly encountered type of crossing in our country. These crossings, which do not have barriers or a control mechanism like a guard, are in the most risky group in terms of traffic safety. In this type of crossings, railway vehicles always have the right of way (TC MEB 2021). In Figure 3.1, an example of a level crossing type without barriers and without a guard is provided.

Figure 3.1. Example of an at-grade crossing without barriers and without a guard (completely uncontrolled) (Bozlioğlu 2017)

The matters that road vehicle drivers should pay attention to when passing through such crossings are provided in the relevant sections of the Road Traffic Law

Figure 3.2. Example of an at-grade crossing without barriers and without a guard (completely uncontrolled) – 2 (Bozlioğlu 2017)

3.2. Barriered Guarded Level Crossings

Especially at grade crossings located within city centers or near busy railway station areas, one of the measures to enhance traffic safety is the installation of barriers at these intersection points and the placement of a guard to ensure the functionality and control of the barrier arm (TC MEB 2021). In Figure 3.3, an example of a level crossing with a barrier and a guard in our country is provided.

In this type of level crossings, all crossing safety conditions are the responsibility of the guard. One of the main duties of the guards is to lower the barrier arms at the crossing at certain intervals, closing the railway line to rail system use and opening it for road vehicles. However, the crossing guard must be alert and vigilant not only during those periods but throughout their entire working hours. This situation is a necessity for the safety of road and rail traffic.

Figure 3.3. Example of a level crossing with a barrier and a guard (Bozlioğlu 2017)

In this type of crossings, there are two situations: locally controlled and remotely controlled. In locally controlled crossings, the person on duty performs their task within a waiting booth established at the crossing site, and the barrier arms are operated by this person, who is referred to as the crossing guard. Level crossing; if it is located near the main switch area on the train line, it is managed by the personnel known as the switchman assigned to the relevant main switch, and if it is within or near the level crossing station area, it is managed by the on-duty movement officer, and this type of crossing is also defined as a remotely controlled crossing (TC MEB 2021).

3.3. Barriered Automatic Controlled Level Crossings

In the type of level crossing with automatic barrier control, the barrier arms are controlled entirely automatically without the need for any crossing guard. They are activated and deactivated automatically when a train approaches at a certain distance, ensuring safety for both road and railway in level crossing areas. Additionally, warning-colored signal lights are also used for all traffic users in these types of level crossing areas. An example of a crossing application is provided in Figure 3.4.

Figure 3.4. Example of a level crossing with barrier and automatic control (Bozlioğlu 2017)

The distribution of level crossing types in our country by region can be seen in Table 3.2.

Table 3.2. Distribution of level crossing types by regions (2020) (TCDD 2021)

Regions	At-Grade Crossing Type				
	Controlled Level Crossing				
	Total	Guarding Barrier	Automatic Barrier	Free (Cross-marked)	Total
1	98	8	90	24	122
2	198	18	180	159	357
3	319	102	217	145	464
4	220	5	215	181	401
5	92	5	87	268	360
6	147	45	102	165	312
7	114	12	102	551	665
Toplam	1188	195	993	1493	2681

4. AT-GRADE (LEVEL) CROSSING SURFACES AND THEIR TYPES

4.1. Ballast – Gravel-Covered Pathways

The inside and sides of the line are filled with ballast or gravel at the level of the rail sleeper and the width of the passage. Ballast or gravel coverings are inexpensive and easy to construct and maintain. However, since it is a soft filling material, when road vehicles pass over the crossing, they skid and cause the undersides of the vehicles to get caught on the rails. Due to vehicles not being able to quickly leave the crossing during the arrival of trains, accidents can occur. In Figure 4.1, an example of a level crossing with a ballast-gravel surface is provided (TC MEB 2008).

Figure 4.1. Ballast-gravel surface level crossing (TCDD 2010)

To fix the railway faults, the crossing surface needs to be completely removed. A lot of labor is required for maintenance. These coatings are greatly affected by vehicle wheels and deteriorate quickly. They are preferably used at level crossings on village roads with very little traffic.

4.2. Rail (Steel) Coated Walkways

The inside and sides of the line are made at the level of the rail bed and the width of the crossing, especially by regularly laying scrap rails. Rail coatings are high-quality coverings applied to heavily trafficked crossings. Additionally, because it is a heavy coating system, it quickly deteriorates in the vertical axis (elevation) of the road, causing subsidence. To repair the railway faults, the crossing surface needs to be completely removed. A lot of labor is required for maintenance. In Figure 4.2, an example of a level crossing with a rail (steel) covering is provided (TC MEB 2008).

Figure 4.2. Rail (steel) clad level crossing (TCDD 2010)

4.3. Wooden Sleeper Coated Walkways

At-grade crossings are constructed by covering the road surface and its edges with wooden sleepers at rail level and the width of the crossing. In this type of covering, the loads from vehicle wheels cause cracks, breaks, and loosening of the connections in the wooden sleeper coverings. Additionally, its use has decreased due to the difficulties in procuring wooden sleepers. It is not economical to use them at level crossings with high traffic where heavy vehicles pass. During road repairs, it is easier to replace, remove, and reassemble the broken and damaged parts. In Figure 4.3, an example of a level crossing with a wooden sleeper covering is provided (TC MEB 2008).

Figure 4.3. Wooden sleeper-covered level crossing (TCDD 2010)

4.4. Concrete-Prefabricated Coated Walkways

At the level crossing, a counter rail is placed at the edges of the tracks to ensure the smooth passage of railway vehicles. The interior and edges of the road are covered with concrete at the level of the rail sleeper and the width of the crossing, either by pouring concrete or placing concrete slabs. Under the wheel impact of road vehicles, the concrete wears down and deteriorates or breaks over time. Because it is difficult and sometimes impossible to repair, it needs to be broken and rebuilt. During road repairs, the passageway needs to be completely broken, causing it to be closed to traffic for an extended period. It is not always possible to find high-strength concrete for the pavement. It is a very difficult and expensive surface to construct, maintain, and use. In Figure 4.4, an example of a level crossing with a concrete-prefabricated surface is provided (TC MEB 2008).

Figure 4.4. At-grade crossing with concrete-prefabricated pavement (TCDD 2010)

4.5. Asphalt-Paved Crossings

The inside and sides of the line are covered with asphalt, which is used on highways, at the level of the rail bed and the width of the crossing. To ensure the smooth passage of railway vehicles, counter rails are placed within the road. Due to the elasticity of the railway, the asphalt deteriorates quickly. If the damaged surface is not repaired in time, it makes it difficult for road vehicles to pass and also causes damage to the railway. Since the asphalt needs to be completely removed for road repair, road traffic is disrupted. However, during road repairs, it is preferred due to its easier removal, the ease of procurement, its long lifespan, and its lower cost and fewer drawbacks compared to other types of pavement. In Figure 4.5, an example of an asphalt-paved level crossing application is provided (TC MEB 2008).

Figure 4.5. Asphalt-paved level crossing (TCDD 2010)

4.6. Rubber-Coated Walkways

All the challenges encountered in practice have pushed railway companies to seek new solutions. As a result of the conducted research, rubber crossing coverings that meet all the needs of the businesses have emerged. Rubber crossing pavement is based on the principle of covering the crossing by arranging rubber pieces of appropriate size and thickness side by side. In

Figure 4.6, an example of a rubber-coated level crossing application is provided (TC MEB 2008).

Figure 4.6. Rubber-coated level crossing (TCDD 2010)

4.7. Cutting – Paved Walkways

The inside and sides of the line are covered with a type of pavement made of cut paving stones, which are used especially on sidewalks, at the level of the rail bed and the width of the crossing, and are used in light rail systems (tram lines). Due to the small surface area of the stone pieces, they cause depressions under the influence of the loads coming onto them. Therefore, they are not used in crossings where vehicles with heavy traffic and high axle loads are used. In Figure 4.7, an example of a level crossing with a cut-stone pavement is provided (TC MEB 2008).

Figure 4.7. At-grade crossing with cut-stone pavement (TCDD 2010)

4.8. Composite Coated Walkways

It is a type of coating made from plastic (polyethylene) or rubber. It is manufactured in three layers with different hardness levels. The softest layer is mounted in the middle. The mounted parts are fastened together with steel rods. However, it is not as elastic as rubber panels. In the applications conducted, it was observed that the layers wore out and broke very quickly, so its use is not widespread.

The statistics of at-grade crossings according to the types of pavement in our country are provided in Table 3.3.

Table 3.3. Level Crossing Types According to Surface Types (2020) (TCDD 2021)

Regions	At-Grade Crossing Type				
	Rubber	Asphalt-Concrete	Paving stone (Keystone)	Other	Total
1	112	10	-	-	122
2	190	20	-	147	357
3	236	63	132	33	464
4	194	125	31	51	401
5	300	10	-	50	360
6	201	25	50	36	312
7	226	22	73	344	665
Total	1459	275	286	661	2681

5. RESULTS

One of the unwanted things in transportation systems is traffic accidents. Estimating and calculating the damage caused by accidents to individuals, operators, and society is quite complex and difficult. When transportation systems are ranked from lowest to highest accident rates, trains and subways come first, followed by trams and road vehicles. Although the train has the lowest accident rate among transportation systems, the majority of these accidents are level crossing accidents. At level crossings, since the likelihood of accidents between road vehicles and railway vehicles is high, the conditions to be sought for the construction of level crossings are as follows:

- The train driver should be able to see the crossing before the braking distance. The minimum distance is 700 meters, and this distance can be increased depending on the road gradient and train speeds.
- Road vehicles should be able to see the railway 250 meters away from both sides of the level crossing.
- There should be a flat area of 50 meters on both sides of the road, and the subsequent slope should not exceed 3-5%. With this slope, it should be connected to the dirt road or highway as much as possible.
- Where the level crossing will be established, there should be no small radius curves and high embankments.
- The angle of intersection between the road and the railway should not be less than 45 degrees.
- The road should cross the railway as perpendicular as possible.

Level crossing areas are also affected by the loads coming from the road along with the railway. Therefore, more frequent malfunctions occur on the railway and road in level crossing areas compared to other road sections.

To prevent these malfunctions and ensure the safety of all railway or road vehicles passing through the crossing, the necessary maintenance in the level crossing areas must be carried out thoroughly.

The maintenance tasks and points to be considered at level crossings are specified below.

The crossing surfaces, barrier mechanism, barrier post, cross warning signs, and barrier balancing weight pits must always be kept clean.

- In passages, the width of the floor gap must be at least 55 mm and the depth at least 50 mm.
- Boden gaps must always be kept clean.
- The road's surface should be well-graded to prevent the hidden voids from damaging the pavement.
- At-grade crossings should be protected from water and its effects. The necessary drainage channels should be opened for this purpose and kept clean at all times.
- In the winter season, snow accumulation and ice formation on the passage should be prevented.
- Objects that obstruct visibility around the pass should not be allowed, and existing ones should be removed as much as possible.

In level crossings with rubber coatings, since the coating pieces rest on the rail base and sleeper, the loads from road vehicles are transferred to the ballast through the sleeper, thus preventing additional damage to the road. Since the coatings can be easily removed and installed, they do not pose a significant problem for road repairs. Plastic parts do not wear out or break easily, as they are resistant to heavy loads and wheel abrasion. Since the rubber part that breaks and gets damaged for any reason is replaced with a new one in a short time, there is no disruption in road traffic.

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COMPARATIVE ANALYSIS OF THIN PLATE BENDING USING ANALYTICAL AND FINITE ELEMENT METHODS

Emre ALPASLAN[1]

1. INTRODUCTION

Plates are essential structural components in a broad array of engineering systems, ranging from civil infrastructure to aerospace and naval applications. Their geometrical characteristic—a relatively small thickness in comparison to their in-plane dimensions—allows them to effectively carry loads primarily through in-plane and bending stresses. Whether found in the floors and walls of buildings, bridge decks, aircraft fuselages, or ship hulls, plates are ubiquitous due to their structural efficiency and ease of fabrication (Ugural, 2009; Szilard, 2020).

When subjected to external loads such as uniform pressure, point forces, or dynamic excitations, plates exhibit complex deformation behaviors that can significantly influence the performance and safety of the entire system. Understanding these behaviors is critical not only for structural integrity but also for serviceability criteria such as deflection limits, vibration characteristics, and fatigue resistance (Altenbach and Eremeyev, 2017). In design scenarios where lightweight and high-strength materials are preferred—such as in aerospace or automotive

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engineering—the need for accurate analysis becomes even more pronounced.

The foundational theoretical model for plate behavior is the classical thin plate theory, originally formulated by Kirchhoff and refined by Timoshenko. This theory makes several simplifying assumptions: the material is linearly elastic, homogeneous, and isotropic; the plate's thickness is small relative to its other dimensions; and the displacements are sufficiently small to neglect geometric nonlinearities. Under these conditions, the transverse normal stress is considered negligible, and cross-sections initially normal to the mid-plane remain so after deformation (Timoshenko & Woinowsky-Krieger, 1959). This classical model, also known as the Kirchhoff–Love theory, provides a powerful analytical framework for many thin-plate problems, especially those with simple boundary conditions and loading scenarios.

However, real-world engineering problems frequently involve complexities that violate the assumptions of classical theory. These include thick plate behavior, material anisotropy (e.g., composites), non-uniform thickness, and non-trivial boundary conditions. To address these challenges, Refined Plate Theories (RPTs)—such as Mindlin-Reissner theory and higher-order shear deformation theories (HSDTs)—have been developed. These models relax some classical assumptions, particularly regarding transverse shear deformation, which becomes significant in moderately thick or layered plates (Reddy, 2007; Kienzler et al., 2004). Despite the theoretical advances, closed-form analytical solutions are often infeasible for practical problems involving irregular geometries or complex loading. In such cases, the Finite Element Method (FEM) has emerged as a versatile and powerful numerical tool. FEM discretizes the domain into smaller subregions (elements), enabling the approximation of complex behaviors with high accuracy. Modern

FEM formulations can accommodate nonlinear materials, dynamic loading, contact mechanics, and even multiphysics problems (Zienkiewicz, Taylor, & Zhu, 2013).

Among commercial FEM software, SAP2000 stands out for its user-friendly interface, robust solver algorithms, and flexible element library. It supports shell elements that combine membrane and bending actions, making it suitable for plate and shell structure modeling. When using FEM for plate bending analysis, the mesh size and aspect ratio of finite elements critically affect the accuracy of the solution. Finer meshes tend to yield more accurate results, especially near boundaries and stress concentrations, but at a higher computational cost. Additionally, square or near-square elements are generally preferred to minimize numerical distortion (Cook et al., 2002; Pisarciuc et al., 2023). Recent studies confirm FEM's effectiveness in both linear and nonlinear plate analysis. Giunta et al. (2023) validated FEM results for variable stiffness composite plates, while Liu et al. (2023) successfully modeled delamination under impact. These works highlight the need to validate numerical models against analytical or experimental data, especially in critical fields like aerospace and marine engineering. Given this context, the present chapter conducts a comparative investigation between the classical thin plate theory and a FEM-based approach using SAP2000. A simply supported rectangular plate under uniform pressure loading is selected as a case study. Analytical expressions for deflection and stress distribution are derived using Kirchhoff plate theory and compared with FEM results obtained from SAP2000 under varying mesh configurations. The objective is not only to assess the accuracy of each method but also to provide practical insights into modeling strategies, mesh design, and result interpretation in engineering practice.

This comparison is particularly valuable for engineering professionals and researchers who must make informed decisions about model fidelity, computational efficiency, and safety margins in structural analysis. By highlighting the limitations and strengths of each approach, the study aims to contribute to the broader understanding of plate behavior under practical constraints and to offer evidence-based recommendations for numerical modeling of plate structures.

2. THIN PLATE BENDING THEORY

The behavior of thin plates under bending loads is a fundamental topic in structural mechanics, with applications in civil, mechanical, and aerospace engineering. The classical thin plate theory offers a simplified yet powerful framework to predict stresses, strains, and deflections in plate elements, provided that the plate is thin, the material is linear elastic, and deformations are small (Timoshenko & Woinowsky-Krieger, 1959; Reddy, 2007).

2.1. Stress and Strain Relationships

Consider a differential element taken from a thin plate subjected to a general state of three-dimensional stress. The primary stresses acting on the element include normal and shear stresses; normal stresses: σ_{xx}, σ_{yy}, σ_{zz}, shear stresses: τ_{xy}, τ_{xz}, τ_{yz}. In classical thin plate theory, the transverse normal stress σ_{zz} is assumed negligible due to the small thickness of the plate. The stresses acting on an element are illustrated in Figure 1.

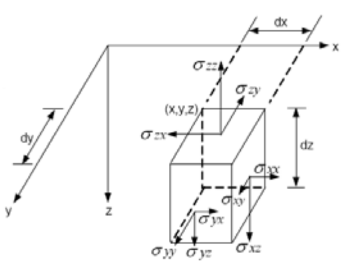


Figure 1. A three-dimensional plate subjected to normal stresses

2.2. Normal and Shearing Strain Components

In the analysis of elastic plate behavior, the strain components play a fundamental role in relating external forces to internal deformations. These strain components are derived based on the theory of linear elasticity under the assumptions of small deformations and isotropic, homogeneous material behavior.

Normal Strains

When a three-dimensional plate is subjected to normal stresses σ_{xx}, σ_{yy}, σ_{zz} the corresponding normal strains in the principal directions are defined as:

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - v\left(\sigma_{yy} + \sigma_{zz}\right)\right] \tag{1}$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - v(\sigma_{xx} + \sigma_{zz})\right] \tag{2}$$

$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - v(\sigma_{xx} + \sigma_{yy})\right] \tag{3}$$

Here:

- ε_{xx}, ε_{yy}, ε_{zz} are the normal strain components in the x, y, and z directions, respectively,
- σ_{xx}, σ_{yy}, σ_{zz} are the normal stresses in the respective directions,
- E is Young’s modulus, and
- ν is Poisson’s ratio.

These equations reflect the generalized Hooke's Law for an isotropic material in three dimensions.

Shearing Strains

In addition to normal deformation, the plate also experiences shearing strains, which arise due to tangential stresses σ_{xy}, σ_{xz}, σ_{yz}. The relationships are expressed as:

$$\varepsilon_{xy} = \frac{\sigma_{xy}}{2G} = \frac{1}{2}\gamma_{xy},\ \varepsilon_{xz} = \frac{\sigma_{xz}}{2G},\ \varepsilon_{yz} = \frac{\sigma_{yz}}{2G} \tag{4}$$

where:

- γ_{xy}, γ_{xz}, γ_{yz} are the engineering shear strains, and
- G is the shear modulus, defined by:

$$G = \frac{E}{2(1+v)} \quad (5)$$

These expressions highlight the linear relationship between shear stress and shear strain in isotropic materials.

2.3. Moment–Curvature Relationships

In the theory of thin plates, internal moments arise due to out-of-plane bending and in-plane torsion of the mid-surface. These internal moments—bending and torsion—are directly related to the curvatures of the deformed plate surface. The mathematical relationships between these moments and curvatures are essential for formulating governing equations in plate bending problems.

2.3.1. Internal Moments on a Plate Element

Consider a differential plate element of unit width and length, as shown in Figure 2. The internal forces acting on this element include:

<u>Bending moments:</u>

M_x: about the x-axis (bending in the x-direction)

M_y: about the y-axis (bending in the y-direction)

<u>Torsional moment:</u>

M_{xy}: acting in the plane, causing torsion

These internal moments result from distributed transverse loads and are assumed positive in the directions indicated in Figure 2a–c.

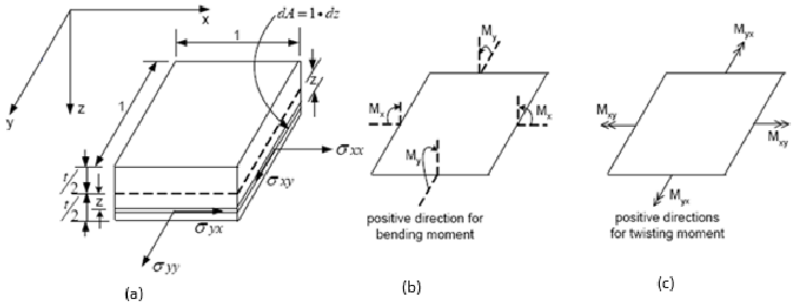


Figure 2. (a) Internal stress components acting on a differential plate element, (b) Positive direction of bending moments, (c) Positive directions of torsional moments

2.3.2. Moment–Curvature Equations

The internal bending and torsional moments are expressed as functions of the transverse displacement field w(x,y) and its second derivatives, which describe the curvature of the plate surface. The relationships are:

Bending moment in x-direction:

$$M_x = -D\left(\frac{\partial^2 \omega}{\partial x^2} + v\frac{\partial^2 \omega}{\partial y^2}\right) \quad (6)$$

Bending moment in y-direction:

$$M_x = -D\left(\frac{\partial^2 \omega}{\partial y^2} + v\frac{\partial^2 \omega}{\partial x^2}\right) \quad (7)$$

Torsional moment:

$$M_{xy} = -M_{yx} = -D(1-v)\frac{\partial^2 \omega}{\partial_x \partial_y} \quad (8)$$

Here, D is the flexural rigidity of the plate, given by:

$$D = \frac{Et^3}{12(1-v^2)} \quad (9)$$

where:

- E: Young’s modulus

- t: thickness of the plate
- ν: Poisson's ratio

2.3.3. Curvature Definitions

The curvature terms in the equations above represent the second derivatives of the transverse displacement w(x,y). These can be interpreted geometrically as:

Bending curvature in the x-direction:

$$\frac{\partial^2 \omega}{\partial x^2} \quad (10)$$

which measures the rate of change of the slope ∂w/∂x along the x-axis (see Figure 3).

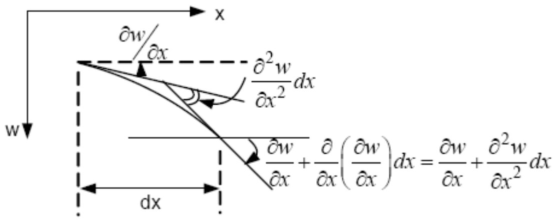


Figure 3. Bending curvature in the x-direction derived from change in slope ∂w/∂x over an interval dx

Torsional curvature:

$$\frac{\partial^2 \omega}{\partial x \partial y} \quad (11)$$

which measures how the slope ∂w/∂x changes along the y-direction (see Figure 4).

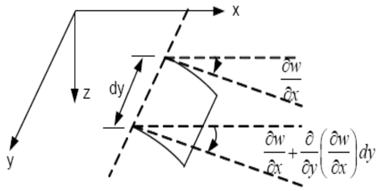


Figure 4. Torsional curvature derived from variation of ∂w/∂x in the y-direction

These curvature components describe how the plate bends and torsions, and directly influence the internal moment distributions. Together with boundary conditions and loading terms, they form the basis of the classical plate equilibrium equation:

$$D\nabla^4 w = q(x, y) \qquad (12)$$

where ∇^4 is the biharmonic operator and q(x,y) is the applied transverse load.

3. APPLICATION FOR A PROBLEM

In this study, a simply supported rectangular plate is considered under uniform pressure loading. The material and geometric properties of the plate are given as follows: Young's modulus E=4350 ksi, applied load q=60 psi, side length a=120 in, thickness t=6 in, and Poisson's ratio ν=0.3. Due to the uniform nature of the pressure and the symmetric boundary conditions, the system exhibits symmetry about both the x- and y-axes passing through the center of the plate. Figure 5 represents the geometry of the simply supported rectangular plate.

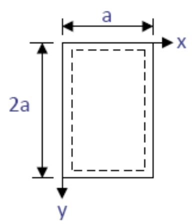


Figure 5. The geometry of the simply supported rectangular plate

As a result, in the analytical formulation based on Fourier series expansion, only symmetric mode shapes contribute to the solution. This symmetry imposes a constraint on the double Fourier sine series such that both mode numbers m and n must be odd integers. Including only odd terms ensures that the deflection surface is symmetric with respect to the plate's centerlines, satisfying both the geometric and loading symmetry conditions. This significantly simplifies the computational effort and improves convergence of the analytical solution.

3.1. Calculation of principal bending moments at the center of the plate

To determine the internal bending behavior of the simply supported plate, the principal bending moments M_x and M_y are calculated at the center of the plate, where x=a/2 and y=a. Owing to the symmetry of the load distribution, only specific sine terms remain non-zero in the Fourier expansion, specifically where $\sin\left(\frac{m\pi x}{a}\right) = \pm 1$ for odd m. The expressions for M_x and M_y are based on double Fourier series solutions derived from classical plate theory. Each term in the summation corresponds to a particular mode interaction, and only odd values of m and n are used due to the symmetry conditions described earlier.

The general expression for M_x at the plate center is:

$$M_x = \frac{16qa^2}{\pi^4} \sum\nolimits_{m,n,odd} (mode - dependent\ coefficients)$$

Substituting values for the material and loading parameters and performing the summation for the first several odd values of m, n=1,3,5, the evaluated series results M_x= 88.363 Kin and M_y=41 Kin.

3.2. Calculation of central deflection of the plate

In addition to bending moment analysis, the transverse deflection w(x,y) of the simply supported rectangular plate under uniform pressure is computed to assess the structural deformation profile. Of particular interest is the central deflection and the deflection behavior along the plate's principal symmetry lines. To provide a detailed understanding of the displacement distribution, deflection values are calculated along two key directions:

$$w(x,y) = \sum_{m=1,3,5}^{\infty} \sum_{n=1,3,5}^{\infty} \frac{16qa^2}{\pi^6 mn\left(m^2 + \frac{n^2}{4}\right)D} sin\frac{m\pi x}{a} sin\frac{n\pi y}{2a}$$

1. Along the centerline in the y-direction: For y=120 in (the mid-span of the plate), deflections are evaluated at x=0, 12, 24, 36, 48, 60, 72, 84, 96, 108, 120 in, which corresponds to points spaced every 12 inches across the x-axis. This allows observation of how the deflection varies from the supported edge toward the center and to the opposite edge along a fixed y-coordinate.

2. Along the centerline in the x-direction: For x=60 in (the mid-span of the plate), deflections are computed at y=0, 24, 48, 72, 96, 120, 144, 168, 192, 216, 240 in, which represents sampling every 24 inches along the y-axis. This provides insight into the deflection pattern across the longer side of the plate at mid-width.

These evaluations aim to capture the complete deformation profile across both axes of symmetry. The resulting deflection values are essential for verifying serviceability criteria and for validating numerical simulations (e.g., FEM models) against classical analytical solutions.

3.3. Calculation of normal and shear stresses

Beyond deflection analysis, it is crucial to evaluate the internal stress distribution within the plate to assess its structural safety under the applied load. In this section, the normal stresses σ_{xx} , σ_{yy} and the in-plane shear stress τ_{xy} are calculated along the centerlines of the plate. The calculations are performed at discrete points—every 12 inches in the x-direction (for y=120 in) and every 24 inches in the y-direction (for x=60 in). Moreover, the stresses are evaluated specifically at the mid-thickness plane z=3 in, i.e., halfway through the plate's 6-inch thickness.

In classical thin plate bending theory, the normal stresses in the x and y directions and shear stress due to bending are expressed using the curvature of the deflection surface:

$$\sigma_x = \frac{Ez}{1-v^2}\left[X_x - vX_y\right] = -\frac{Ez}{1-v^2}\left[\frac{\partial^2\omega}{\partial x^2} - v\frac{\partial^2\omega}{\partial y^2}\right]$$

$$\sigma_y = \frac{Ez}{1-v^2}\left[X_y - vX_x\right] = -\frac{Ez}{1-v^2}\left[\frac{\partial^2\omega}{\partial y^2} - v\frac{\partial^2\omega}{\partial x^2}\right]$$

$$\tau_{xy} = \frac{Ez}{1-v}X_{xy} = -\frac{Ez}{1-v}\frac{\partial^2\omega}{\partial x\partial y}$$

The curvature terms $\frac{\partial^2 w}{\partial x^2}, \frac{\partial^2 w}{\partial y^2}, \frac{\partial^2 w}{\partial x\partial y}$ are derived using double Fourier sine and cosine series expansions, due to the simply supported boundary conditions and the symmetric nature of the uniform load. These are given by the following expressions:

Bending curvature in x-direction:

$$\frac{\partial^2 w}{\partial x^2} = -\sum_{m=1,3,5}^{\infty}\sum_{n=1,3,5}^{\infty}\frac{16*q*a^2}{D*\pi^4}\frac{m^2}{m*n*(m^2+\frac{n^2}{4})}sin\frac{m*\pi*x}{a}sin\frac{n*\pi*y}{2a}$$

Bending curvature in y-direction:

$$\frac{\partial^2 w}{\partial y^2} = -\sum_{m=1,3,5}^{\infty}\sum_{n=1,3,5}^{\infty}\frac{16*q*a^2}{D*\pi^4}\frac{n^2}{4*m*n*(m^2+\frac{n^2}{4})}sin\frac{m*\pi*x}{a}sin\frac{n*\pi*y}{2a}$$

Torsional curvature:

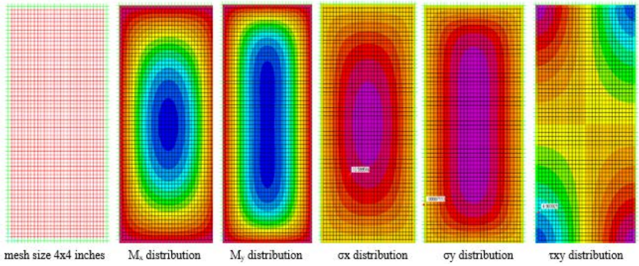
$$\frac{\partial^2 w}{\partial x\partial y} = -\sum_{m=1,3,5}^{\infty}\sum_{n=1,3,5}^{\infty}\frac{16*q*a^2}{D*\pi^4}\frac{m*n}{2*m*n*(m^2+\frac{n^2}{4})}cos\frac{m*\pi*x}{a}cos\frac{n*\pi*y}{2a}$$

These series are typically truncated after a few dominant terms (e.g., m, n=1,3,5) to achieve practical computational efficiency without significant loss of accuracy. The computed stress values along the two symmetry axes provide valuable insight into maximum stress locations and allow direct comparison with allowable material limits for design verification.

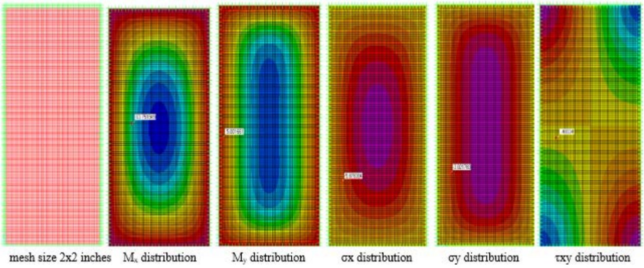
3.4. Finite Element Analysis and Mesh Sensitivity Study

In this section, finite element simulations are conducted to investigate the influence of mesh size and element aspect ratio on the accuracy of numerical results. The plate is modeled in

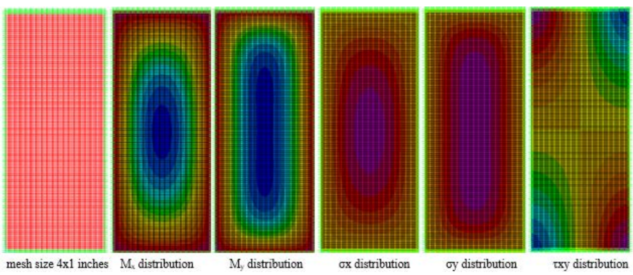
SAP2000 using shell elements, and three distinct mesh configurations are analyzed (Figure 6).



(a)



(b)



(c)

Figure 6. Mesh size and moment and stress distributions in each cases (a) case 1, (b) case 2, (c) Case 3

Case 1 employs a coarse square mesh with 4×4-inch elements, resulting in 1800 elements and an aspect ratio of 1.0, ensuring geometric uniformity and isotropic stiffness. Case 2 uses a finer square mesh with 2×2-inch elements, totaling 7200 elements, also with an aspect ratio of 1.0; this higher density is expected to improve accuracy, particularly for capturing stress gradients and localized deformations. Case 3 adopts a rectangular mesh with 4×1-inch elements and a high aspect ratio of 4.0, totaling 7200 elements. While this configuration maintains high mesh density, the elongated shape of the elements may introduce numerical anisotropy and affect bending behavior predictions.

The rationale for analyzing these three cases is to evaluate the sensitivity of finite element results to changes in mesh density and aspect ratio. By comparing the numerical outcomes—particularly deflections and bending moments—with those from the analytical solution, the effectiveness and limitations of each mesh configuration can be assessed. This comparative approach provides practical insight into how to balance computational cost with result fidelity in structural plate modeling.

4. COMPARION of RESULTS

4.1. Comparison of Bending Moments: Analytical vs. Finite Element Solutions

Table 1 presents a comparative evaluation of the bending moments at the center of the plate obtained from the analytical (hand) calculations and the finite element method (FEM) under three mesh configurations: Case 1 (coarse square mesh), Case 2 (fine square mesh), and Case 3 (rectangular mesh with high aspect ratio). The goal is to assess the accuracy and mesh sensitivity of the FEM models with respect to the analytical reference values.

Table 1. Comparison of moments at the center of plates

	Hand Calculation	Finite Element Calculations					
		Case 1	Error (%)	Case 2	Error (%)	Case 3	Error (%)
Mx (K*in)	88.363	87.8083	0.627	87.86262	0.566	87.8589	0.571
My (K*in)	41.000	40.023	2.383	40.2418	1.849	40.2428	1.846

The analytical solution yields Mx=88.363M_x = 88.363Mx=88.363 and My=41.000M_y = 41.000My=41.000, serving as a benchmark for evaluating FEM accuracy. Case 1 (4×4 in mesh) shows errors of 0.63% for M_x and 2.38% for M_y, suitable for preliminary design but less accurate. Case 2 (2×2 in mesh) improves accuracy with errors of 0.57% and 1.85%, showing convergence with mesh refinement. Case 3 (4×1 in mesh, aspect ratio 4) achieves similar accuracy to Case 2, confirming that high mesh density can compensate for non-square geometry. Overall, all cases align closely with the analytical solution (errors < 2.5%), but mesh density has a greater impact than element shape. Case 2 offers the best balance of efficiency and precision.

4.2. Comparison of Deflections

Figure 7 compares deflections w(x,y) along the x-axis centerline (y=120 in) and y-axis centerline (x=60) for a simply supported rectangular plate, using analytical results and three FEM mesh configurations: Case 1 (4×4 in, 1800 elements), Case 2 (2×2 in, 7200 elements), and Case 3 (4×1 in, aspect ratio 4, 7200 elements). All FEM results closely follow the analytical trend, with maximum deflection errors at the plate center around 1.4% for all cases. Minor deviations at other points (e.g., 12, 24, 108 in) remain under 3.3%, with most under 1.5%. Despite Case 3's higher aspect ratio, its accuracy is comparable to Case 2, highlighting that mesh density is more influential than element shape. Overall, Cases 2 and 3 are well-suited for detailed engineering analyses, while Case 1 is sufficient for preliminary evaluations.

4.3. Comparison of Stresses

Figure 8 compares the normal stress component σ_{xx} along the x-axis centerline (y=120 in) and y-axis centerline (x=60 in) of a simply supported plate, using analytical results and three FEM mesh configurations: Case 1 (4×4 in), Case 2 (2×2 in), and Case 3 (4×1 in, aspect ratio 4). The maximum compressive stress at the center (x=60, y=120 in) is −14.7301 ksi with FEM deviations under 0.7% for all cases. At other points, errors generally remain below 1.2%, and often under 0.5%, confirming strong agreement. Boundary points yield zero stress as expected, validating correct implementation. Overall, all FEM models replicate the analytical distribution accurately, with Case 2 offering the best balance of precision and efficiency, and Case 3 showing that fine rectangular meshes can perform equally well.

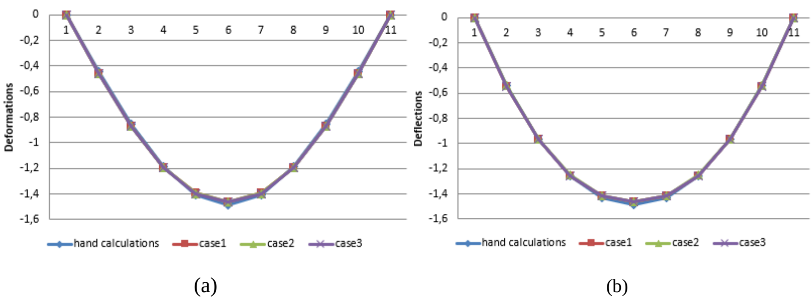


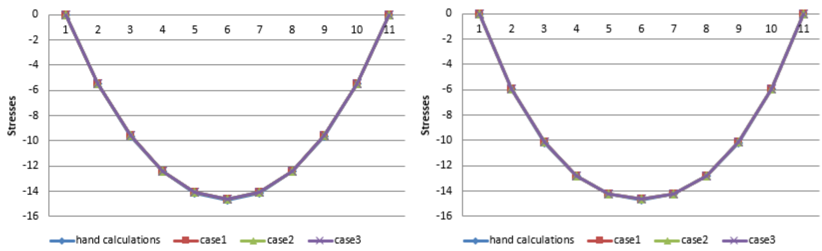
Figure 7. Comparison of deflections along (a) x direction (b) y direction

4.4. Comparison of Stresses

Figure 8 compares the normal stress component σ_{xx} along the x-axis centerline (y=120 in) and y-axis centerline (x=60 in) of a simply supported plate, using analytical results and three FEM mesh configurations: Case 1 (4×4 in), Case 2 (2×2 in), and Case 3 (4×1 in, aspect ratio 4). The maximum compressive stress at the center (x=60, y=120 in) is −14.7301 ksi with FEM deviations under 0.7% for all cases. At other points, errors generally remain below 1.2%, and often under 0.5%, confirming strong agreement. Boundary points yield zero stress as expected, validating correct implementation. Overall, all FEM models replicate the analytical distribution accurately, with Case 2 offering the best balance of precision and efficiency, and Case 3 showing that fine rectangular meshes can perform equally well.

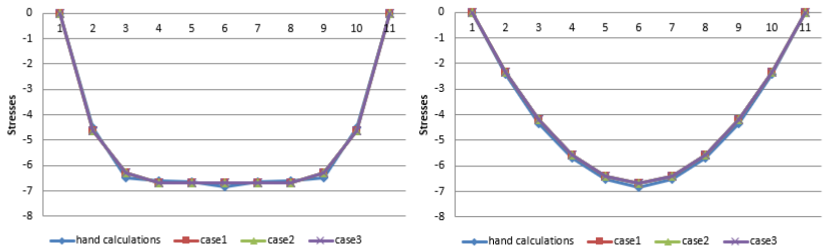
Figure 9 compares the normal stress component σ_{yy} along the x-axis centerline (y=120 in) and y-axis centerline (x=60 in) between analytical and FEM results for three mesh configurations. The maximum stress occurs at the plate center, where FEM models slightly underestimate the analytical value ($\sigma_{yy}=-6.8323$ ksi) with errors around 2.3% for all cases. Along both axes, most FEM errors range between –2.7% and 3.4%, with highest deviations at x=24 in, yet maintaining reasonable accuracy. The boundary values correctly return zero stress, confirming appropriate support implementation. Overall, FEM results for σ_{yy} are in good agreement with analytical values, with all cases yielding errors under 3.5%, demonstrating sufficient accuracy for engineering use.

Figure 10 presents a comparison of the shear stress component τ_{xy} along the x-axis centerline (y=120 in) and y-axis centerline (x=60 in) between analytical and FEM results for three mesh configurations. Across all cases, FEM values show excellent agreement with analytical results, with maximum errors remaining below 1.2%. The largest deviations are observed near points of stress inflection (e.g., y=96 in), but even then, the discrepancies are minor. Errors are mostly under 0.6% along the x-axis and under 1.2% along the y-axis, demonstrating that all FEM meshes -including the high-aspect-ratio Case 3- accurately capture shear stress variation. The symmetry of the stress distribution and zero values at the plate center and edges are also correctly represented. Overall, FEM predictions of τ_{xy} show high numerical fidelity, with all three mesh types delivering reliable results suitable for engineering applications.



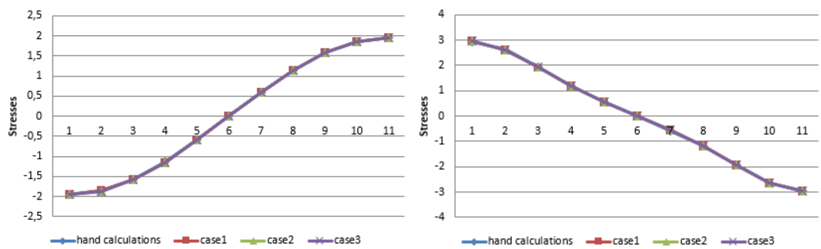
(a) (b)

Figure 8. Comparison of σxx along (a) x direction (b) y direction



(a) (b)

Figure 9. Comparison of σyy along (a) x direction (b) y direction



(a) (b)

Figure 10. Comparison of τxy along (a) x direction (b) y direction

5. CONCLUSION

Based on the comparative results, all three FEM mesh configurations demonstrate strong agreement with analytical solutions for bending moments, deflections, and stress components. Maximum deviations remain below 3.5%, with most errors under 1.5%, confirming the validity of the numerical models. Among the configurations, Case 2 (fine square mesh) offers the best balance between computational efficiency and accuracy, while Case 3 (rectangular mesh with high aspect ratio) performs nearly as well due to its high mesh density. Case 1 (coarse mesh) is adequate for preliminary analysis but less reliable for precision modeling. Overall, the study confirms that mesh density has a greater impact on solution accuracy than element aspect ratio, and both Case 2 and Case 3 are recommended for detailed engineering simulations.

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CONSTRUCTION SITE LOGISTICS AND SUPPLY CHAIN MANAGEMENT

Casim YAZICI[1]

1. INTRODUCTION

The construction industry has long been characterized by its project-based, fragmented, and resource-intensive nature. Unlike other manufacturing sectors, construction projects are subject to high levels of uncertainty, complex stakeholder interactions, and dynamic on-site conditions. In this environment, the effective integration of information, time, labor, and material resources becomes paramount. As such, construction site logistics and supply chain management (SCM) have emerged as critical enablers of project performance, offering substantial benefits in terms of cost efficiency, timely delivery, and overall sustainability.

Construction logistics goes beyond the mere transportation of materials and equipment. It involves the orchestration of multiple operations, including workforce allocation, material procurement, site layout planning, inventory control, safety compliance, and environmental considerations. Delays in material deliveries, improper resource scheduling, or inefficient layout planning can trigger cascading failures that affect not only the physical flow but also the financial and temporal health of the project. Hence, logistics must be understood as a strategic, integrative function that necessitates

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coordination among site engineers, project managers, procurement officers, and suppliers alike (Arshad & Zayed, 2022).

The concept of supply chain management in construction encompasses both upstream and downstream activities ranging from raw material sourcing and pre-fabrication to on-site assembly and commissioning. This end-to-end perspective is essential for managing risks, ensuring quality, and meeting client expectations. In recent years, global disruptions, price volatility in building materials, and increased complexity in construction networks have underscored the importance of proactive, data-driven SCM strategies (Ding & Jie, 2025).

Digitization is revolutionizing construction logistics and SCM through technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and blockchain. These technologies enable enhanced transparency, traceability, real-time monitoring, and predictive planning. In particular, the adoption of modular and prefabricated construction has significantly altered the nature of logistics workflows, necessitating more synchronized and centralized planning tools (Chen, Fan & Ma, 2025; Liu, Zhang & Zhang, 2024).

Against this backdrop, this chapter aims to present a comprehensive examination of the fundamental concepts, current practices, and emerging innovations in construction site logistics and supply chain management. Drawing upon a curated selection of contemporary studies, the chapter seeks not only to highlight prevailing challenges but also to offer forward-looking strategies for enhancing operational resilience and sustainability in the construction sector.

2. FOUNDATIONS OF CONSTRUCTION SITE LOGISTICS

2.1. Material Flow and Site Accessibility

The efficient flow of materials to and from the construction site is a cornerstone of successful logistics operations. In practice, this involves synchronizing the delivery schedules with construction phases to avoid congestion, idle times, and double handling. A poorly timed delivery can obstruct essential pathways or delay critical tasks, compromising both productivity and safety. Technologies such as RFID and GPS-based systems facilitate real-time visibility and dynamic coordination of deliveries, providing site managers with actionable data to respond to unforeseen disruptions (Liu, Zhang, & Zhang, 2024).

In urban construction projects where spatial constraints are significant, material flow planning must also account for accessibility and off-site staging areas. Just-in-time logistics strategies, supported by digital platforms, can substantially reduce the need for large on-site inventories, thus freeing up space for other operational activities. Moreover, an integrated material tracking system enables the identification of bottlenecks and supports lean construction practices, which aim to maximize value while minimizing waste.

2.2. On-Site Resource Coordination

Effective logistics requires precise coordination of workforce, machinery, and materials. Labor scheduling tools and collaborative planning platforms ensure that the right personnel and resources are available as needed. Misalignment between site needs and resource availability can create bottlenecks that impact downstream construction activities (Chen, Fan & Ma, 2025).

2.3. Logistics Space Management

Given the limited space on most construction sites, proper layout planning is essential. Designating storage zones, access routes, and assembly areas improves operational efficiency and safety. Digital twin simulations and lean layout methodologies have shown promise in reducing waste and optimizing spatial arrangements (Arshad & Zayed, 2022).

2.4. Labor and Equipment Scheduling

Timely deployment and relocation of equipment and personnel affect workflow continuity. Integrated scheduling tools that align manpower needs with equipment availability prevent idle time and resource underutilization. Predictive analytics also play a role in identifying potential conflicts or gaps in site operations (Chen, Fan, & Ma, 2025).

2.5. Health, Safety, and Environmental Considerations in Construction Logistics

Construction logistics must also account for health and safety protocols as well as environmental impacts. This includes managing access to the site, ensuring safe routes for transportation, monitoring hazardous zones, and maintaining regulatory compliance. Noise reduction measures, dust suppression systems, and proper waste segregation are also essential elements. Recent studies suggest integrating these dimensions into the overall logistics strategy through smart monitoring tools and simulation platforms to ensure proactive risk mitigation (Ding & Jie, 2025).

3. SUPPLY CHAIN MANAGEMENT AND DIGITALIZATION

Supply chain management (SCM) in the construction industry is no longer perceived as a peripheral function but has evolved into a central strategic operation. This shift is driven by the growing complexity of construction projects, increased client expectations, and the rising demand for sustainable, timely, and cost-effective project delivery. The decentralized and fragmented nature of construction work necessitates robust SCM systems capable of coordinating multiple suppliers, contractors, and logistical operations across different geographies and timelines.

Digitalization plays a transformative role in this context. With the advent of Building Information Modeling (BIM), Internet of Things (IoT), artificial intelligence (AI), and blockchain technologies, traditional supply chains are evolving into interconnected digital ecosystems. These technologies enable real-time data exchange, predictive planning, and transparency across all stages of the project lifecycle. BIM, for instance, supports virtual construction sequencing and material forecasting, while IoT sensors provide continuous feedback on equipment utilization, environmental conditions, and site productivity (Chen, Fan, & Ma, 2025).

One of the most significant shifts in construction SCM is the increased reliance on off-site prefabrication and modular building systems. These approaches emphasize the importance of timing and precision in the delivery and installation of building components. Any mismatch between fabrication and on-site readiness can disrupt the entire workflow. Hence, supply chain resilience and coordination become crucial elements. Liu, Zhang & Zhang (2024) highlight that AI-enabled forecasting and scheduling algorithms are instrumental in minimizing such disruptions.

Blockchain technologies have also begun to address long-standing issues of trust, payment disputes, and documentation errors within construction supply chains. By enabling immutable, time-stamped records, blockchain facilitates transparent and verifiable transactions between stakeholders. This reduces administrative overhead and enhances accountability throughout the procurement and delivery process (Chen, Ma & Fang, 2025). Looking ahead, quantum computing holds potential to revolutionize logistics optimization by processing vast data sets at speeds unattainable by classical systems. Although still emerging, its application in route planning, resource allocation, and schedule simulation is expected to further streamline operations and enhance responsiveness (Chen, Ma, & Fang, 2025).

Nevertheless, the integration of these digital technologies is not without barriers. Many construction firms face challenges such as inadequate IT infrastructure, limited digital literacy, and resistance to organizational change. Overcoming these barriers requires strategic investment in workforce training, change management, and collaboration with technology providers. These technological trends are not just futuristic concepts; they are actionable tools already reshaping how projects are planned and delivered.

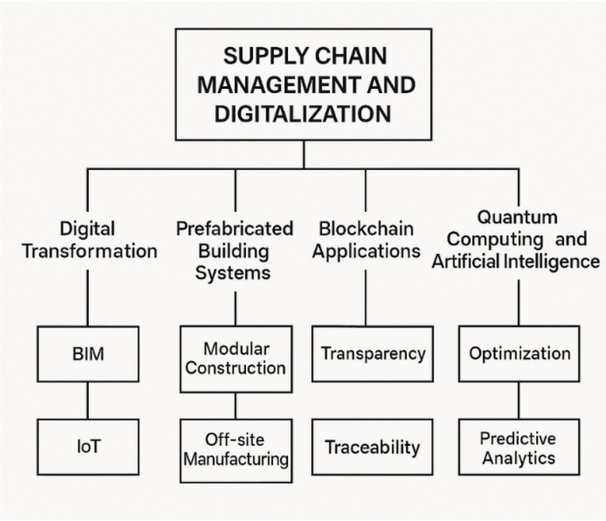

Figure 1. Core elements of digitalized construction supply chains.

Their integration into logistics frameworks offers a path forward for building more resilient, adaptive, and efficient construction supply chains. Construction logistics must also account for health and safety protocols as well as environmental impacts. This includes managing access to the site, ensuring safe routes for transportation, monitoring hazardous zones, and maintaining regulatory compliance. Noise reduction measures, dust suppression systems, and proper waste segregation are also essential elements. Recent studies suggest integrating these dimensions into the overall logistics strategy through smart monitoring tools and simulation platforms to ensure proactive risk mitigation (Ding & Jie, 2025).

4. RISK AND UNCERTAINTY MANAGEMENT IN SUPPLY CHAINS

Uncertainty is an inherent attribute of the construction industry due to its reliance on external conditions such as weather, labor availability, material volatility, transportation disruptions, and market dynamics. These variables introduce significant unpredictability into both planning and execution phases of construction projects. As a result, the ability to anticipate, absorb, and recover from disruptions has become a defining competency in modern construction supply chains.

Risk and uncertainty management in supply chains is therefore not merely a support function but a strategic imperative. Disruptions can occur at any node of the supply chain-from procurement and production to transport and on-site delivery and can have ripple effects across project activities. The increasing integration of global supply networks, while beneficial in terms of cost and efficiency, has made construction logistics more exposed to international uncertainties including geopolitical risks, customs delays, and pandemics. To address these challenges, firms must adopt a proactive approach that includes continuous risk monitoring, scenario-based forecasting, and strategic buffer management.

Construction supply chains are particularly susceptible to disruptions such as delayed shipments, supplier insolvency, regulatory changes, natural disasters, and site-specific constraints. Traditional reactive supply chain strategies that rely on post-incident responses are insufficient in today's fast-paced and interconnected project environments. As highlighted by Ding and Jie (2025), effective supply chain risk management requires a shift toward proactive identification, prioritization, and mitigation of risks through systemic analysis.

Modern risk management increasingly leverages digital tools to support early detection and agile responses. Predictive analytics can assess deviations in planned versus actual progress, flagging issues before they escalate. Machine learning algorithms analyze historical project data to forecast potential delays or cost overruns. In parallel, simulation tools and digital twins enable virtual stress-testing of logistics plans under various disruption scenarios. These capabilities contribute to more resilient supply chains by providing insight into vulnerability points and enabling corrective actions in advance.

Collaboration is another vital enabler of risk management. Integrated project delivery (IPD) models and shared platforms such as BIM enhance transparency, coordination, and trust among stakeholders. These structures facilitate joint risk identification and allow for faster realignment of resources in the event of unforeseen changes. Figure 2 shows a layered framework based on risk origin.

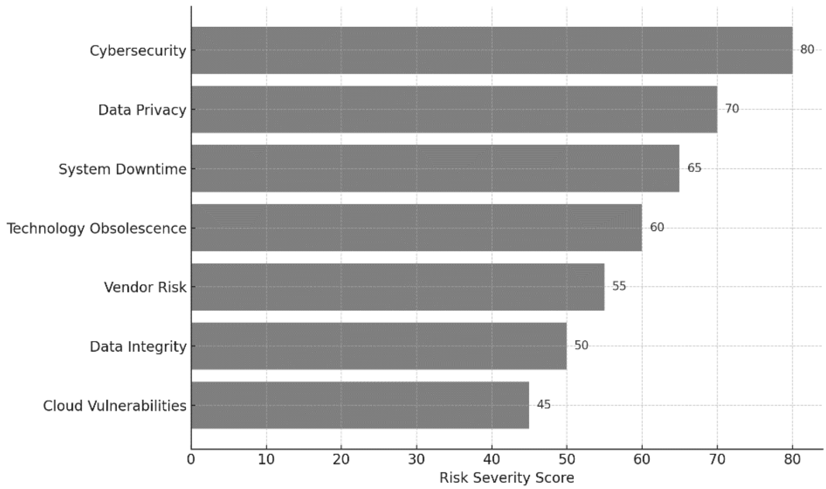

Figure 2. highlights digital risk domains in SCM.

Figure 3. illustrates risks in reverse logistics.

To institutionalize resilience, firms should promote a culture of risk awareness, invest in regular risk training programs, establish early warning systems, and adopt flexible procurement and contracting models. These practices allow organizations to transition from reactive systems to adaptive supply networks capable of maintaining continuity and performance under stress. These practices transition supply chains from reactive systems to adaptive networks capable of sustaining performance under stress.

5. CIRCULAR ECONOMY AND REVERSE LOGISTICS

Circular economy principles are gaining prominence in the construction industry as stakeholders seek sustainable ways to reduce waste, extend material life cycles, and optimize resource use. Traditional linear models of 'take-make-dispose' are being replaced with regenerative systems where waste is viewed as a resource. Reverse logistics plays a critical role in this transition by enabling the return, reuse, remanufacture, or recycling of materials within construction supply chains.

In construction, reverse logistics can involve the collection and return of reusable components such as scaffolding, formwork, pallets, and temporary structures. It also includes the processing of demolition waste for recycling or repurposing. Efficient reverse logistics systems contribute to reduced material costs, lower landfill use, and enhanced environmental compliance. They require coordination between contractors, suppliers, waste processors, and local authorities.

Technological tools support these systems by providing visibility and control. RFID and GPS tracking technologies allow real-time monitoring of materials as they move in reverse along the supply chain. Blockchain systems add accountability by recording each transaction and transfer point securely. Predictive analytics help optimize collection schedules and processing workflows. Strategically, reverse logistics fosters innovation in product design, encouraging modular construction and easy disassembly. It also supports circular procurement strategies where contractors select suppliers based on their ability to provide recyclable or reusable materials. By embedding reverse logistics into supply chain planning, firms can align operational goals with sustainability objectives. Figure 4 shows a basic model of reverse logistics in construction.

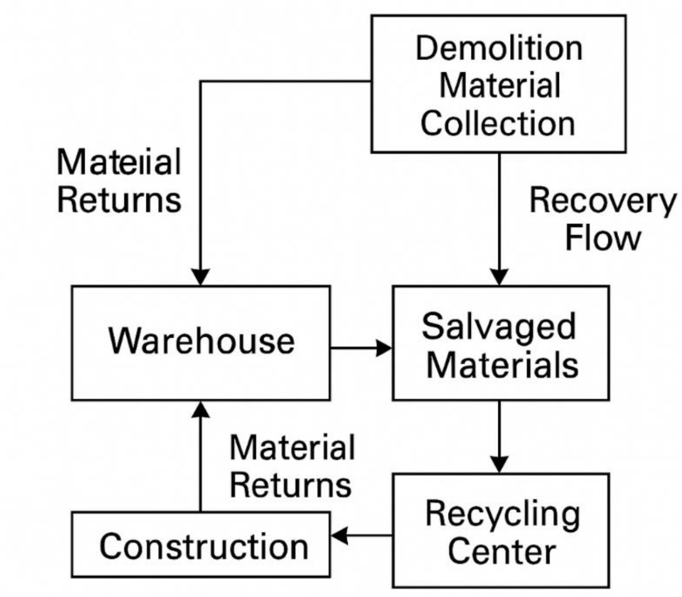

Figure 4. Reverse logistics model in construction

6. FUTURE DIRECTIONS AND STRATEGIC RECOMMENDATIONS

As the construction industry evolves under the pressures of globalization, digital transformation, and climate urgency, the logistics and supply chain management (SCM) landscape must adapt accordingly. The future of construction SCM lies in building integrated, intelligent, and resilient systems that not only deliver efficiency but also align with broader environmental and social goals.

One key direction is the deeper integration of artificial intelligence and machine learning into logistics decision-making. Beyond simple forecasting, AI tools will increasingly support prescriptive analytics, automatically suggesting optimal delivery schedules, inventory levels, and equipment allocation strategies. This evolution will enable real-time responsiveness and continuous improvement across logistics operations.

Another trend is the proliferation of platform-based collaboration. As demonstrated by the growing adoption of Building Information Modeling (BIM) and cloud-based project management systems, future supply chains will become increasingly transparent, enabling multiple stakeholders to access and contribute to shared data environments. This transparency not only facilitates coordination but also enhances accountability.

In terms of sustainability, future supply chains will be expected to meet stricter carbon accounting and material traceability standards. This includes incorporating lifecycle assessments into procurement processes, adopting green logistics practices, and expanding circular economy models through extended producer responsibility and reverse flows.

Furthermore, organizations will need to invest in digital skills development and leadership training to effectively navigate the shift toward high-tech supply networks. Strategic partnerships with technology providers, academic institutions, and government agencies will be critical in scaling innovation across the sector.

Finally, resilience must remain a central theme. As global disruptions such as pandemics, cyberattacks, and extreme weather events become more common, supply chains must be designed to anticipate and recover from shocks. This involves not only technical measures but also governance frameworks that embed flexibility, redundancy, and scenario planning into organizational routines.

By embracing these strategic directions, the construction industry can transform its logistics and supply chain functions into sources of competitive advantage, capable of delivering value, agility, and sustainability in an increasingly complex world.

7. CONCLUSION

Construction logistics and supply chain management are undergoing a profound transformation shaped by technological innovation, sustainability imperatives, and the need for greater resilience. The review of recent literature indicates that digitalization, circular economy models, and risk-aware planning are no longer optional strategies but essential components of successful project execution.

Digital tools such as BIM, RFID, and predictive analytics are enabling real-time monitoring, better coordination, and proactive decision-making, while circular practices like reverse logistics are helping minimize waste and reduce environmental impacts. At the same time, the increasing complexity and volatility of global supply chains call for robust risk management frameworks that can anticipate, absorb, and adapt to disruptions.

The construction sector must continue investing in integrated platforms, workforce capabilities, and innovative partnerships to remain competitive and sustainable. By adopting these multidimensional strategies, the industry can build supply chains that are not only efficient but also intelligent, transparent, and aligned with broader societal goals.

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ESKİŞEHİR'DE KENTİÇİ RAYLI SİSTEM ÇALIŞMALARI[1]

Şafak BİLGİÇ[2]

M. Korkut ARBERK[3]

1. GİRİŞ

Kentsel ulaştırmada amaç, bir yandan kentte yaşayanların günlük ulaşım gereksinimlerini en uygun biçimde karşılarken, diğer yandan da kentsel gelişme hedeflerine uyarlanması kolay olan uyumlu bir ulaşım politikası izlemektir. Hızla artan nüfus ve araç sahipliği sebepleriyle artan trafik sıkışıklığı sorunlarını azaltmak için en uygun çözümün toplu taşıma sistemlerine öncelik vermek olduğu açıktır. Bu sebeple, ulaşım sorunlarının çözülmesi için uzun dönemli çalışmalar ağırlıklı olarak değerlendirilmelidir. Bu çözümler mevcut ulaşım yapısının daha verimli çalışabilmesi için yapılması gereken düzenlemeleri ve belirlenen hedef yılında oluşacak yolculuk talebinin toplu taşıma ağırlıklı bir ulaştırma sistemiyle karşılanabilmesi için yapılması gerekli ulaşım yatırımlarını içermelidir. Bu ulaşım yatırımları genellikle çok yüksek yatırım maliyetlerine sahip olduklarından etüt aşaması oldukça önemlidir. Halkın ulaşım ihtiyaçlarını karşılayabilecek kapasitedeki bir sistem, mümkün olduğunca düşük maliyetle gerçekleştirilmeye çalışılmalıdır. Ancak burada

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[1] BİLGİÇ, Ş., (1996), Eskişehir Kentiçi Toplu Taşımacılığında kullanılacak Hafif Raylı Taşıt Özelliklerinin Belirlenmesi, Eskişehir Osmangazi Üniversitesi Fen Bilimleri Enstitüsü Yüksek Lisans Tez Çalışmasından üretilmiştir.

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sadece yatırım maliyetinin değil, uzun vadede oldukça önem arz eden işletme maliyetlerinin de gözönüne alınması gerekmektedir. Bugün dünyada birçok büyük şehir, kentiçi ulaşımı için raylı sistemlere yönelmektedir. Kentiçi raylı sistemlerin ilk örneği 1832'de New York Harlem'de atlar tarafından çekilen tramvaydır. İkinci ise 1835'te New Orleans'ta işletmeye açılmıştır ve bu hat halen elektrikli araçlarla hizmete devam etmektedir. 1920'lere kadar tüm dünyada raylı sistemler hızla yaygınlaşırken, 1930'lardan itibaren özel otoların sayısının hızla artışı ve raylara ve elektrik hatlarına ihtiyaç duymadığından güzergâhlar bakımından daha esnek olan lastik tekerlekli otobüslerdeki gelişmeler raylı sistemlerin sayısının giderek azalmasına sebep olmuştur. Özellikle de II. Dünya Savaşı'ndan sonra gelişmiş ülkelerdeki refah düzeyinin yükselmesi özel araçların genel bir ihtiyaç olarak algılanmasına yol açmış ve bu da toplu taşımaya olan talebi azaltmıştır. Ancak 1970'lerle beraber çok sayıda özel aracın yol açtığı trafik ve çevre sorunları büyük problemler yaratmaya başlamış ve toplu taşımanın önemi anlaşılmaya başlanmıştır. 1970'lerde tekrar gözde olan toplu taşıma sistemleri arasında raylı sistemler de yerlerini almıştır. Bugün dünyada birçok büyük ve orta büyüklükteki şehirde raylı sistem bulunmakta, bazılarında ise bu konudaki çalışmalar devam etmektedir (Taplin, 2025; Bilgiç, 1996).

2. ESKİŞEHİR İLİNE AİT GENEL BİLGİLER

Eskişehir, İç Anadolu Bölgesi'nin kuzeybatısında, Eskişehir ovasının güneybatı kesiminde kurulmuş ve ovaya doğru genişlemiş olan bir kenttir. Sakarya nehrinin kolu olan Porsuk Çayı kentin içinden geçmekte ve ovayı sulamaktadır.

19. yüzyıl başlarında Bilecik’e, 19. Yüzyıl sonlarında ise Kütahya’ya bağlı olan küçük bir kasaba olan Eskişehir’i toplumsal ve ekonomik açıdan en fazla etkileyen olay,

demiryolunun Eskişehir'e ulaşması ve buradan Konya ve Ankara'ya doğru devam etmesi olmuştur. Haydarpaşa'dan gelen ilk tren 19 Haziran 1892'de Eskişehir istasyonuna ulaşmıştır. Kurulan Cer Atölyesi çok sayıda Eskişehirliye iş alanı açmış, buradan yetişen gençler daha sonra yeni kurulan fabrikalarda yetişmiş eleman olarak çalışmışlardır (Koylu, 2008).

Demiryolu hattının ovadan geçişi ile tarihi Odunpazarı bölgesinde yoğunlaşmış olan yapılaşma, hızla ovaya doğru yayılmaya başlamıştır.

Cumhuriyetin ilanından iki yıl sonra il merkezi olan Eskişehir'de, sanayi, ildeki tarımsal ve doğal potansiyeller değerlendirilecek şekilde bu yıllarda gelişmeye başlamıştır. Bu dönemde kent, güneydeki eski yapısını koruyan mahalleler ile kuzeydeki demiryolu arasında yayılmıştır. 1970'li ve 1980'li yıllarda kentin gelişimiyle, kentsel rant hızla artmış ve şehir ovaya doğru büyümeye devam etmiştir. Bu yüzden gelişmekte olan sanayi sektörü kent merkezinden uzak bölgelere kaymaya başlamıştır. 1970'lerin başında Ankara karayolu üzerinde, kentten 12 km uzakta kurulan Organize Sanayi Bölgesi, şehrin ekonomik gelişim tarihinde önemli bir mihenk taşıdır. Bu dönemde, karayolları, konut gelişimini beraberinde getirmiş, Eskişehir'i çevre yerleşim merkezlerine bağlayan yollar boyunca yapılaşma artmıştır. Eskişehir'in İstanbul, Ankara ve İzmir şehirlerine yakınlığı ve ulaşımının kolaylığı bu şehirlerin etkisinde kalmasına yol açmıştır. Böylece Eskişehir daha çok Orta Anadolu ile Batı Anadolu'daki yerleşim merkezleri arasında iletişimi sağlayan bir köprü ve kendi bölgesindeki ekonomik faaliyetleri düzenleyen bir şehir durumuna gelmiştir. Kentin fiziksel gelişimindeki en önemli sorun, tarımsal açıdan son derece değerli olan ova toprağının, tarımsal amaçlı kullanımının kentsel rantla rekabet edemeyip şehre katılmasıdır. Diğer ova kentlerimizin de karşı karşıya kaldığı bu durum sonucunda tarımsal açıdan değerli olan araziler telafisi olamayacak şekilde kaybedilmektedir.

Kentin gelişimi üzerindeki önemli etkenlerden biri olan ulaşım ağının planlanmasında bu durum gözönüne alınmalıdır (Bilgiç, 1996).

Eskişehir 1892 yılından beri ülkemizin önemli bir demiryolu kavşak noktasıdır. Eskişehir'in Türkiye demiryolu ulaşım ağında önemli bir yeri bulunmaktadır. Ankara, İstanbul ve İzmir demiryolu hatlarının kesişim noktasında bulunan Eskişehir, 2009 yılında Yüksek Hızlı Tren sisteminin ilk kullanıma girdiği şehir de olmuştur. Kentin içinden geçen demiryolu hattının yer altına alınma çalışmaları 2014 yılında tamamlanmıştır. Tren Garı şehir merkezinde oldukça önemli bir konumda bulunmaktadır.

Eskişehir'in 2023 yılsonu nüfusu 915.418'dir. TÜİK'e göre ilin nüfusu 2000 yılından sonra her yıl ortalama %1,15 oranında artmıştır. Eskişehir'de ilçe nüfusları homojen dağılmamaktadır. İldeki 14 ilçeden 12'sinin nüfusu 25.000'in altında iken, Tepebaşı ve Odunpazarı merkez ilçelerinin nüfusu 400.000 civarındadır. Tepebaşı ve Odunpazarı ilçeleri Eskişehir nüfusunun önemli bir bölümünü (yaklaşık %89) barındırmaktadır. En fazla nüfusa sahip olan Odunpazarı ilçesinin nüfusunun toplam nüfus içindeki payı %46,04 iken Tepebaşı ilçesinin payı %42,62'dir. Eskişehir'in ilçelerinin nüfus değerleri Tablo 1'de verilmiştir.

Eskişehir merkez ilçelerde (Odunpazarı ve Tepebaşı) önemli bir öğrenci nüfusu ve kent içi hareketliliği etkileyen turist sirkülasyonu da bulunmaktadır. Bu nedenle, merkezi bölgelerdeki nüfus artış tahminleri ve toplu taşıma talepleri dikkate alınarak, toplu taşıma hizmetinin daha çevre dostu tramvay sistemiyle sağlanmasının daha uygun olacağı düşünülmüştür. Şehir merkezi için TÜİK'e göre 2023 yılı nüfusu ve 2035 yılı için hazırlanan Eskişehir Ulaşım Ana Planına (EUAP 2035) göre 2025, 2030 ve 2035 yılı öngörüleri Tablo 2'de verilmiştir.

Tablo 1. Eskişehir ilçelerindeki nüfus değerleri (TÜİK, 2023)

İlçe	Nüfus	Pay (%)
Odunpazarı	421.469	46,04
Tepebaşı	390.116	42,62
Sivrihisar	20.478	2,24
Çifteler	14.926	1,63
Seyitgazi	13.481	1,47
Alpu	10.678	1,17
Mihalıççık	8.576	0,94
Mahmudiye	7.715	0,84
İnönü	6.244	0,68
Beylikova	6.016	0,66
Günyüzü	5.679	0,62
Sarıcakaya	4.651	0,51
Mihalgazi	3.037	0,33
Han	2.352	0,26
TOPLAM	915.418	100,00

Tablo 2. Eskişehir merkez ilçelerindeki nüfus değerleri (EUAP 2035, 2017; TÜİK, 2024)

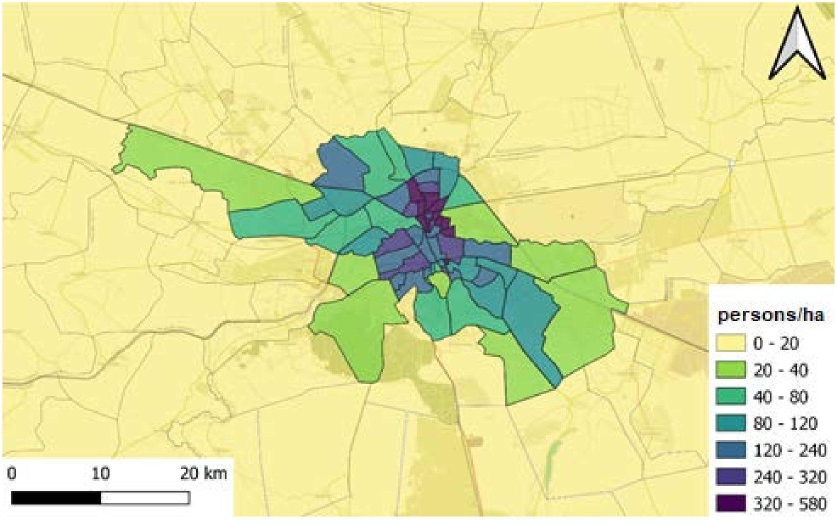
Merkez İlçeler (Odunpazarı + Tepebaşı)	TÜİK, 2023	EUAP 2035		
	2023	2025	2030	2035
Nüfus	811.585	1.073.429	1.222.326	1.298.802

1965 yılında il nüfusunun yaklaşık %59'u il merkezinde yaşarken bu oran sürekli artarak 2023 yılında %89'a ulaşmıştır (Tablo 3). EUAP 2035'e göre kent merkezinde ve merkez çevresinde yer alan mahalleler günümüzde belirli bir nüfus doluluğuna ulaştığından, artması beklenen nüfusun gelecekte kent planlarının öngördüğü gibi merkezdeki mahallelere göre daha düşük yoğunluklu planlı alanlara yerleşeceği öngörülmektedir. Eskişehir kent merkezinde nüfus yoğunluğu oldukça yüksektir. Eskişehir ilinin mahallelerinin 2015 yılı nüfus yoğunlukları Şekil 1'de verilmiştir (TÜİK, 2024).

Tablo 3. Eskişehir ilçelerinin nüfus değişimi (TÜİK, 2024)

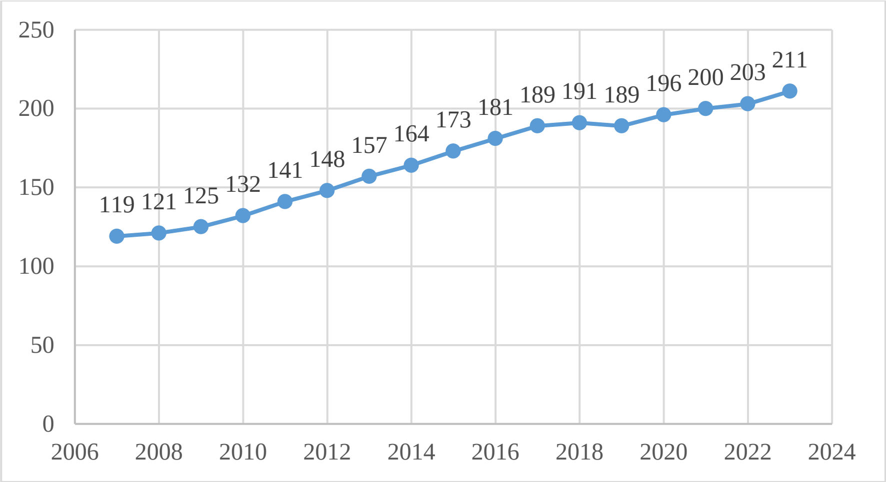
	1965	1980	1990	2000	2010	2015	2023
Merkez İlçe	243.033	373.988	447.926	519.602	-	-	-
Alpu*	-	-	18.679	16.727	12.768	11.526	10.678
Beylikova*	-	-	10.946	10.506	6.562	6.091	6.016
Çifteler	23.306	25.649	20.073	18.545	16.716	15.232	14.926
Günyüzü*	-	-	15.310	16.508	7.025	5.970	5.679
Han*	-	-	4.277	3.681	2.165	1.959	2.352
İnönü*	-	-	9.377	9.331	7.228	6.822	6.244
Mahmudiye	12.984	12.045	11.267	10.132	8.770	7.987	7.715
Mihalgazi*	-	-	9.059	14.029	3.876	4.507	3.037
Mihalıççık	42.271	37.191	24.088	18.696	10.482	8.850	8.576
Sarıcakaya	13.527	14.277	7.996	14.968	5.642	5.678	4.651
Seyitgazi	26.372	24.691	24.762	21.701	16.222	13.753	13.481
Sivrihisar	53.608	55.961	37.297	31.583	23.488	21.265	20.478
Odunpazarı*	-	-	-	-	358.713	383.523	421.469
Tepebaşı*	-	-	-	-	284.927	333.553	390.116
TOPLAM	**415.101**	**543.802**	**641.057**	**706.009**	**764.584**	**826.716**	**915.418**
Merkez Nüfusunun Toplam İl Nüfusuna Oranı (%)	58,5	68,8	69,9	73,6	84,2	86,7	88,7

** Alpu, Beylikova, Günyüzü, Han ve Mihalgazi 1987 yılında, Odunpazarı ve Tepebaşı ise 2008 yılında ilçe olmuştur.*



Şekil 1. 2015'teki nüfus yoğunlukları (kişi/ha) (EUAP 2035, 2017)

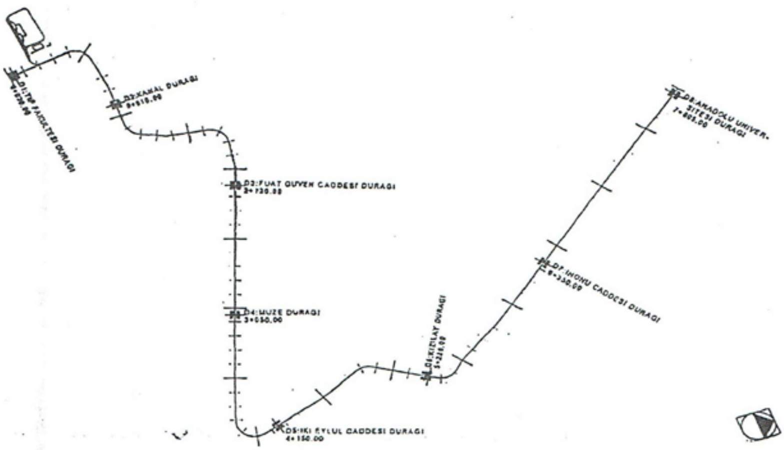
Eskişehir'de otomobil sahipliği özellikle 1990 yılından sonra önemli ölçüde artmıştır. Özel otomobil sahipliği 1980 yılında 1000 kişi başına 18 iken 1990 yılında 1000 kişi başına 34'e yükselmiştir. Ancak 1990 yılından sonra hızlı bir artış gösteren otomobil sahipliği değeri 1997 yılında 76 otomobil/1000 kişiye, 2012 yılında ise 148 otomobil/1000 kişiye yükselmiştir. Ekim 2015 sonu itibariyle Eskişehir'de trafiğe kayıtlı özel otomobil sayısı 141.187, toplam motorlu taşıt sayısı ise 244.346'dır. Trafiğe kayıtlı özel araç sayısının 2000 yılında 67.239, toplam motorlu araç sayısının ise 104.741 olduğu düşünüldüğünde, 15 yılda nüfusun %15, otomobil sayısının %110, toplam motorlu araç sayısının ise %133 arttığı görülmektedir. 2023 yılı sonunda trafiğe kayıtlı motorlu taşıt sayısı 339.274'e ulaşmıştır. EUAP 2004'te 2020 yılı için öngörülen 170 otomobil/1000 kişi seviyesine 2015 yılında ulaşılmıştır. TÜİK verilerine göre, otomobil sahipliği 2023 yılında 211 otomobil/1000 kişi seviyesine ulaşmıştır (Şekil 2). EUAP 2035'e göre bu değerin 2035 yılında 305 otomobil/1000 kişiye ulaşacağı öngörülmektedir (Bilgiç vd., 2024).



Şekil 2. Eskişehir ili için yıllara göre otomobil sahipliği (otomobil/1000 kişi) (TÜİK, 2024)

3. ESKİŞEHİR İÇİN RAYLI SİSTEM ÇALIŞMALARI

Eskişehir'in özellikle kent merkezinde yaşanan yoğun trafik nedeniyle gündeme gelen raylı sistemle ilgili tartışmalar uzun yıllar önce başlamış ve hızla artan nüfus gözönüne alınarak bir raylı sistem için çalışmalara ve planlamalara geç kalınmadan başlanması hakkında genel bir fikir birliği oluşmuştur. Bu konudaki çalışmalar ise esas olarak Eskişehir Büyükşehir Belediyesi tarafından 1995 yılında ODTÜ Ulaşım Araştırma Merkezi'ne yaptırılan Eskişehir Ulaşım Master Planı ile başlamıştır. Bu çalışmada Eskişehir'deki ulaşım durumu genel özellikleriyle ortaya konulmuş ve kent merkezinde bazı caddelerin tek yönlü yapılması ve kentin iki üniversitesi arasında ve şehir merkezinden de geçen bir Hafif Raylı Sistem önerisi yapılmıştır. Önerilen bu güzergah Şekil 3'de gösterilmiştir.



Şekil 3. Eskişehir Ulaşım Master Planında önerilen HRS hattı (1995)

Önerilen Hafif Raylı Sistem, Osmangazi Üniversitesi Tıp Fakültesi önünden başlayıp bu tür bir sistem için yeterli genişlikteki Hasan Polatkan Bulvarı (bugünkü Atatürk Bulvarı) boyunca ilerleyip, bir aç-kapa tünelle Odunpazarı bölgesini geçip, İki Eylül Caddesi üzerinden Köprübaşı'na ulaşmaktadır. Burada Porsuk Çayını 391 metrelik bir köprülü kavşakla geçip İsmet İnönü Caddesi üzerinden Demiryolu ve Çevreyolu'nu mevcut üstgeçitlerle geçerek Anadolu Üniversitesi Eczacılık Fakültesi önünde son bulmaktadır. Bu güzergah toplam 7850 metredir ve hemzemin kavşaklar dışında kendi tahsisli yolunda çalışması öngörülmüştür. Sistem için tahsisli hattında balastlı, sinyalize hemzemin kavşaklarda balastsız bir hat, ilk işletme yılında ikili, talep artışı paralelinde üçlü araçlar, 25 km/sa ticari işletme hızı, 4 dakika zirve saat dizi zaman aralığı, 7,5 dakika normal saatte dizi zaman aralığı, 20 dakika seyrek saatte dizi zaman aralığı, işletmede 18 araç ve 2 yedek araç ve güç kaynağı için ise 750 V DC havai hat önerilmiştir. Sistemin mevcut hat ve araç sayısı önerileriyle kapasitesi 8400 kişi/saattir (Bilgiç ve Karacasu, 1999).

Ancak önerilen bu sistem yüksek maliyeti ve aşağıda sıralanan diğer nedenlerden dolayı yerel yetkililer ve sivil toplum kuruluşlarınca kabul görmemiştir:

- Porsuk Çayı geçişi için önerilen 391 metrelik ve 4,50 m yüksekliğindeki köprünün yapılması halinde kentin bu en merkezi noktasında çirkin bir beton yığını görüntüsü oluşacağı düşünülmüştür,
- Hafif Raylı Sistem için tahsisli hat yapılması durumunda özellikle kent merkezinde araç trafiği için büyük sıkıntılar doğacağı öngörülmüştür,
- Özellikle İsmet İnönü Caddesinden geçiş, mevcut araç trafiğini tek şeride indireceğinden uygun görülmemiştir.

Bu projenin yukarıdaki sebepler ve mali sorunlar nedeniyle uygulamaya geçirilememesine rağmen bu konudaki tartışmalar devam etmiş ve bir kamuoyu oluşmuştur. Bu konuda çeşitli toplantılar da düzenlenerek konunun tartışılmasına devam edilmiştir.

Eskişehir'in kentiçi ana arterleri oldukça dar olduğundan daha çok tahsisli hat gerektiren Hafif Raylı Sistemin şehrin yapısına uygun olmadığı düşünülmüştür. Sistemin tamamının yeraltında veya viyadükler üzerinde yapılmasının da yüksek maliyet sebebiyle zor olacağı değerlendirilmiştir. Eskişehir gibi orta büyüklükteki, ancak kent merkezindeki yapılaşma eski ve caddeleri dar olan şehirlerde bu derece iddialı yatırımların yapılması oldukça zordur. Bu şartlar altında en uygun çözümün tramvay sistemi kurmak ve kent merkezinde diğer araçlarla aynı yolu paylaşmasına izin vermek olacağı fikri ortaya çıkmıştır. Burada asıl problem ise kurulacak sistemin sahip olacağı hatların belirlenmesi olarak ortaya çıkmıştır. Sistemin esas amacı, genellikle şehrin dış mahallelerinden şehir merkezine gelecek ve daha sonra geri dönecek olan yolcuları, mevcut otobüs sisteminin yol açtığı trafik sorunlarına yol açmadan taşımak olduğundan, sistemin, en yoğun otobüs geçişine sahip olan noktalar arasında kurularak, bu noktalardan dizi halinde geçen otobüslerin ikame edilmesi hedeflenmiştir.

Eskişehir Büyükşehir Belediyesi tarafından İstanbul Teknik Üniversitesine yaptırılan Ulaştırma Ana Planı 2004 yılında tamamlanmıştır. Bu plan Büyükşehir Belediye Meclisi tarafından 2004 yılında onaylanmıştır.

Eskişehir Büyükşehir Belediyesi bu plana uygun olarak modern bir tramvay sistemi inşa edilmesi için Bombardier-Yapı Merkezi Konsorsiyumu ile 9 Mayıs 2002 tarihinde bir yapım ve temin sözleşmesi imzalamıştır. 2004 yılında Uluslararası Raylı Sistemler Birliği'nin Hafif Raylı Sistem Ödülünü kazanan ESTRAM, 24 Aralık 2004 tarihinde hizmete açılmıştır.

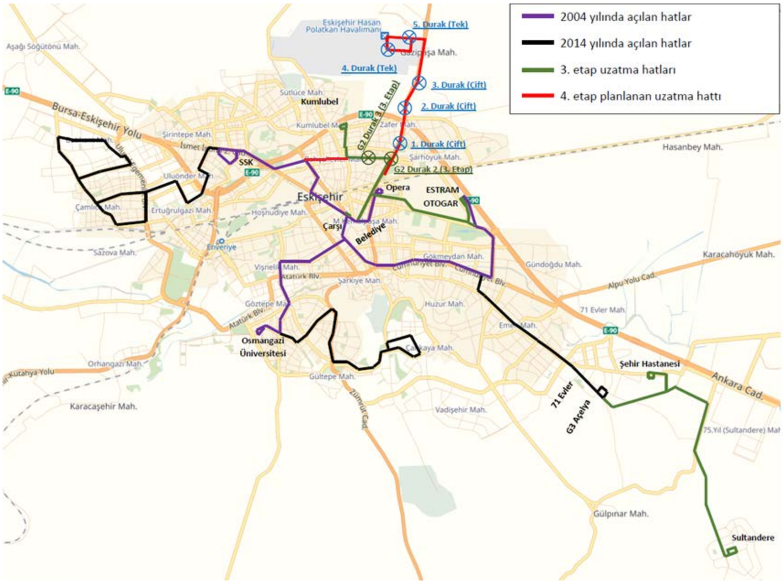
ESTRAM, Otogar, SSK, OGÜ ve Opera olmak üzere 4 uç noktasına sahip olarak 16 kilometrelik hatla hizmet vermeye başlamıştır. (EUAP 2004, 2004).

ESTRAM'ın 2. etap projesi için 13 Ocak 2012 tarihinde Gülermak-YDA Ortaklığı ile sözleşme imzalanmıştır. 18 Nisan 2012 tarihinde kazıya başlanmış ve Emek-71 Evler hattı 18 Mart 2014 tarihinde, Batıkent-SSK ve Çamlıca-SSK ring hatları 08 Ağustos 2014 tarihinde, Çankaya-OGÜ ring hattı ise 17 Ağustos 2014 tarihinde işletime açılarak toplam 33 tramvay ile 7 hatta hizmet verilmeye başlanmıştır.

08 Haziran 2018'de temeli atılan 3. etap projesiyle Şehir Hastanesine ve Sultandere ile 75. Yıl mahallelerine uzatma planlanmıştır. Ayrıca Opera uç noktasından Ömerağa, Tunalı, Fatih ve Kumlubel Mahallelerini kapsayacak bir hat uzatması tasarlanmıştır. Otogar-Opera bağlantısı, SSK Kolunun Yıldıza bağlanması ve Yıldız-Opera kolunun çift hat yapılması da bu proje kapsamına dâhil edilmiştir.

3. Etap hatlarından Şehir Hastanesi kısmı öncelikli olarak tamamlanmış ve 10 Mart 2019'de işletime başlanmıştır. 12 Mart 2021'de ise 75. Yıl-Sultandere kolu tamamlanmış olup 75. Yıl – OGÜ hattında yolculu işletime başlanmıştır. Kumlubel kolunun tamamlanması ile 14 Haziran 2021'de Şehir Hastanesi - Kumlubel hattında işletime başlanmıştır. Son olarak 06 Ocak 2025 tarihinde Kentpark, Şeker ve İsmail Gaspıralı Duraklarını kapsayan Otogar-Opera-OGÜ hattında sabah ve akşam yolculu tramvay seferleri başlatılmıştır.

3.Etap projesinin tamamlanmasının ardından yaklaşık 55 kilometrelik işletme hattına (depo ve park hatları hariç) sahip olan ESTRAM, 47 araçla planlanan 9 hatta Eskişehirlilere hizmet vermeye devam etmektedir (Şekil 4, Tablo 4) (ESTRAM, 2025).



Şekil 4. Mevcut ve planlanan hatlar için tramvay sistemi güzergah haritası

Tablo 4. Tramvay sistemi hatları ve hafta içi sefer sıklıkları

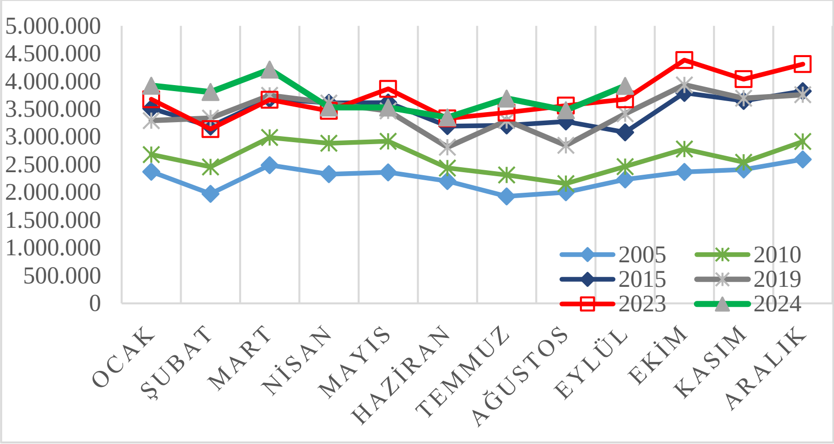
Hat Numarası	Hat Adı	Hafta içi gündüz saatlerinde kalkış sıklığı (dakika)
1	Otogar-SSK	8
3	Osmangazi Üni.-SSK	8
4	Otogar-Osmangazi Üni.	16
7	Osmangazi Üni.-Çankaya	20
8	SSK-Batıkent	18
9	SSK-Çamlıca	18
10	Şehir Hast.-Kumlubel	10
12	75.Yıl-Osmangazi Üni.	27
36	Otogar - Opera - Osmangazi Üni.	-

Şekillerden de görüleceği üzere raylı sistem hatları şehir merkezinde kesişen ve toplu taşıma sisteminin omurgasını oluşturan hatlar olarak planlanmış, otobüs ve minibüs hatları ise bu omurgayı destekleyen ve besleyen güzergahlar olarak düzenlenmiştir.

2004'ün sonunda faaliyete geçen tramvay sistemi ile 2005 yılında 27.269.153 kişi taşınırken, bu değer 2023 yılında yaklaşık 44,6 milyona ulaşmıştır.

Okulların kapalı olduğu Şubat, Temmuz ve Ağustos aylarında taşınan yolcu sayısı en aza inmektedir. Tramvay seferlerinin aylara göre dağılımı Şekil 5'te grafik olarak gösterilmiştir. Şeklin çok fazla karışmaması ve verilerin daha iyi görülebilmesi için sadece 5 yılın grafiği verilmiştir. Yıllar içinde değişimin daha iyi görülebilmesi için 2005, 2010, 2015, 2019, 2023 ve 2024 verileri seçilmiştir.

Eskişehir tramvay sisteminin 4. etabı olarak Gaffar Okkan Caddesi'nin bitiş noktasından başlayıp Eskişehir Teknik Üniversitesi İki Eylül Yerleşkesine ulaşacak hattın ve Seylap (Aytaç) Caddesi boyunca geçen hattın yapılması planlanmaktadır. Yaklaşık 5,8 km uzunluğundaki bu hatların inşasından sonra EUAP 2035'te önerildiği gibi HR/3 kodlu Osmangazi Üniversitesi-ESTÜ tramvay seferleri ve HR/4 kodlu SSK-ESTÜ tramvay seferleri yapılabilecektir. Böylece kentteki 3 üniversitenin de ana yerleşkeleri tramvay hattı ile ulaşılabilir hale gelecektir (Bilgiç vd, 2024).



Şekil 5. Tramvay sistemiyle yapılan yolculukların aylık dağılım grafiği

4. SONUÇLAR

Eskişehir kent merkezinde büyük trafik sorunlarına yol açan otobüslerin ve otomobillerin kent merkezine girmesini önlemek amacıyla planlanan ve 2004 yılından beri kent merkezine ana erişim yöntemi haline gelen ESTRAM tramvay sistemi, yıllık 45 Milyon civarında yolcu taşıyan, 55 kilometrelik hatta ve 47 araca sahip bir sistem haline gelmiştir. Sistemin ağ olarak genişletilmesi ve yeni satın alınacak araçlarla daha fazla yolcuya hizmet vermesi planlanmaktadır.

Kent trafiğine sağladığı büyük faydalara rağmen ESTRAM sistemine iki ciddi eleştiri yapılmaktadır: Araçların aşırı kalabalık olması ve eşdüzey kavşaklarda karayolu trafiğini uzun süre bekletmesi. Bu konuda daha önce kurulacak tramvay sisteminin iki araçlı diziler şeklinde çalışması şeklindeki öneriler en baştan uygulansaydı bugün çok daha az sorun yaşanacağı açıktır (Bilgiç ve Karacasu, 1999).

ESTRAM sistemi sebebiyle kavşaklarda oluşan trafik sorunlarının çözümü için bir diğer öneri ise tramvay hattının yeraltına alınmasıdır. Ancak zemin kotu ile -5 metre arasında bulunan içme suyu, kanalizasyon, telefon, elektrik, fiber optik vb altyapıların deplase edilmesi oldukça zor ve masraflı olacaktır. Bu sebeple ikili veya üçlü diziler ile kapasite artışı yapılması ve daha az dizinin kavşaklardan geçişinin sağlanması çok daha akılcı bir çözüm olacaktır. İleride kapasitenin yetersiz olması ve kavşaklardaki trafik sorunlarının artması durumunda -5 metre ile -10 metre arasında açılacak bir tünelli raylı sistem ile destek verilebilir. Bu durumda tramvay sefer sayıları azaltılabilir.

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AKADEMİK PERSPEKTİFTEN

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